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URBAN RESILIENCE BASED SYSTEMS MANAGEMENT

Merging the concepts of community and infrastructure resilience

A thesis submitted in fulfilment of the requirements for the Degree of Doctor of
Philosophy

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DECLARATION

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Conor Mark Dowling

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ABSTRACT

As a result of climate change cities face challenges of growing complexity and uncertainties including increasing magnitude and volume of droughts, storms and flooding among other extreme weather events. Traditional risk management, based on probabilistic quantitative methods, are no longer sufficient to address the unpredictability and magnitude of these events. These challenges are further complicated by the increased interdependency of many of society's urban systems which presents a fundamental challenge to even the most comprehensive risk analysis. In response to this problem urban resilience has grown in popularity as a way to address the impacts of climate change and to maintain the functionality of urban systems during disaster events. However urban resilience remains siloed in its application to either built infrastructure systems or the communities they support and there is a significant gap in the literature as to how these two resilience types can be brought together.

The early integration of resilience into the design of critical infrastructure systems management is needed to complement the existing knowledge-base of risk analysis and to address the emerging issues associated with complexity and uncertainty. This thesis argues for the significance of resilience in urban development and the necessity for practitioners to engage with the emerging concept of viewing critical infrastructure as part of a wider complex socio-technical system (STS). The research aims to develop and trial professional approaches to embed resilience within design processes through an empirical contribution with the development of a Resilience Management Framework (RMF). This framework aims to provide decision makers with a baseline measurement of STS resilience and suggests how resilience capabilities may be improved. The framework is tested with a case study which helps to develop practical pathways to resilience attainment. This study is complemented by expert interviews which aim to elicit effective and practical approaches to the implementation of conditions for urban resilience. The study identified sources of resilience and resilience dynamics that require management in the context of STS management. The thesis is concluded with a discussion on the importance of new professional tools for facilitating the delivery of resilient systems and with the conclusions of the study.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

α	Alpha, reorganisation phase of the adaptive cycle
Ω	Omega, collapse or release phase of the adaptive cycle
BCR	Benefit Cost Ratio
CAS	Complex Adaptive System
CAQDAS	Computer Assisted Qualitative Data Analysis Software
CBA	Cost-Benefit Analysis
CI	Critical Infrastructure
CIP	Critical Infrastructure Protection
CONNECT	The Science Foundation Ireland Research Centre for Future Networks and Communications
DCC	Dublin City Council
DHS	Department of Homeland Security
DRI	Disaster Resilience Indicators
DROP	Disaster Resilience of Place (model)
ED	Electoral Division
EPA	Environmental Protection Agency
EU	European Union
FAC	Future Analytics Consulting
GIS	Geographic Information System
IAIP	Information Analysis and Infrastructure Protection
ICARUS	Irish Climate Analysis and Research Units
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardization
K	Conservation phase of the adaptive cycle
KRNW	Knowledge Resource Nomination Worksheet
LPWAN	Low Power Wide Area Network
NBS	Nature-Based Solutions
NUIM	National University of Ireland Maynooth
OPERANDUM	Open-air laboratories for nature based solutions to manage environmental risks
OPW	Office of Public Works

QGIS	Quantum Geographic Information System
R	Growth or exploitation phase of the adaptive cycle
RESILENS	Realising European Resilience for Critical Infrastructure
RMF	Resilience Management Framework
RQ	Research Question
S(1-6)	Stage (1-6)
SMS	Short Message Service
SOTA	State Of The Art
STS	Socio-Technical System
SUDS	Sustainable Urban Drainage Systems
TCD	Trinity College Dublin
UCD	University College Dublin
UN	United Nations
UNISDR	United Nations Office for Disaster Risk Reduction (acronym updated to UNDRR)
VT	Vizor Technology (Sigfox Ireland)

CHAPTER 1 INTRODUCTION

This chapter introduces the main themes of the thesis and provides an overview of the research. Section 1.1 presents the general background and rationale for the research. Section 1.2 identifies the research problem. Section 1.3 sets out the propositions, research questions and study objectives. Finally, Section 1.4 presents an overview of the thesis structure.

1.1 Background

‘Cities are complex systems and [climate related] shocks are often both the causes and the effects of the current conditions of urban communities. The more vulnerable the community, the greater it may be affected. A resilient city is able to maintain a continuity of services and functions throughout any shock or stress, while protecting and enhancing people’s lives. However, an effective and comprehensive definition and method of measuring a city’s resilience capacity is still missing.’ (EU Commission, 2019).

This is the opening statement of the European Commission’s statement on the European Union (EU) strategy on adaptation to climate change. It encapsulates the rationale behind the Commission’s efforts to make improving urban resilience a strategic priority for the EU. The Commission’s focus on developing policies toward mitigating the impacts of climate change across the economic, environmental and social spheres is a response to the complex and interdependent nature of urban systems.

In December 2015, the Paris Climate Agreement resulted in a global consensus on the need to act on climate change with governments putting forward clear mitigation policies and actions to reduce their carbon output. A total of 195 countries, including Ireland, agreed to the legally binding global climate deal to reduce their emissions. While this may be seen as a step towards combatting climate change the impacts of human activities cannot be reversed in the short term. These impacts will be significant for countries across the globe, including Ireland. The increasing rate and scale of climate-related flooding events is consistent with projections as well as regional and

global trends (Thomas and López, 2015; EPA, 2008). This is illustrated by the myriad extreme weather events in Ireland in recent years, including the major flooding in Cork city in 2009, the severe flooding in Donegal with bridges and roads being washed away in August 2017, and to the recent the drought in summer 2018. The impact of climate-related disasters poses significant risks for all of the essential services on which our modern society depends. Critical infrastructure (CI) such as the transport network, water supply, energy (electricity and fuel) systems, and communications services, are all at risk. The 100 Resilient Cities (2017) EU prospectus states that *‘aging infrastructure, extreme weather, and mass migration disproportionately affect urban centres and will only continue to further impact them’*. Climate change will have a wide-ranging impact on the Irish society, economy, and environment, in addition to their embedded CI systems. CI supports the day to day operations of cities including societal, environmental and economic functions, and it is essential that these services are protected during extreme weather events.

Despite the development of new climate legislation, including the National Climate Mitigation Plans and National Adaptation Frameworks (DCCAE, 2017), there is a significant risk that adequate measures to ensure the impacts of climate change will not be sufficient to mitigate the effects of climate-related disasters in Ireland. The Capital Investment Plan for 2016-2021 (DPER, 2015) set out a budget of €27 billion euro for all infrastructure and capital investment over a six-year period. This equates to 2% of GDP compared to an EU average of 2.9%. Compounding the threats posed by climate change the International Monetary Fund has identified that although Ireland has median quality levels in terms of European infrastructure, there are deficiencies in relation to comparable peer countries with investment needed in CI. Since the global downturn in 2008, Ireland’s economy has recovered well. However, a burgeoning economy and growing population will place further demands on CI, which is already reaching capacity (Engineering Ireland, 2017). The inadequacy of the current investment in CI is further compounded by increasing populations relying on outdated infrastructure. As a response to the threat of climate change, improving the resilience of urban communities, so that they are capable of withstanding, adapting and recovering from disruptive events, is paramount.

The word resilience has been originated from the Latin ‘resiliere,’ which translates as ‘to bounce back’. The common use of resilience implies the ability of an entity or system to return to its ‘normal’ condition after the occurrence of a disruption event. This general definition has been adapted and applied to a diverse range of fields including ecology, engineering, psychology, social science, economics, and business management. Some general definitions of resilience that span multiple disciplines have been offered in Table 1.1.

Author(s) & Discipline	Definition
Alberti et al.(2003) Environmental Science	“... the degree to which cities tolerate alteration before reorganizing around a new set of structures and processes” (p. 1170).
Godschalk (2003) Engineering	“... a sustainable network of physical systems and human communities” (p. 137).
Ernstson et al.(2010) Social Science	“To sustain a certain dynamic regime, urban governance also needs to build transformative capacity to face uncertainty and change” (p. 533).
Ahern (2011) Environmental Science	“... the capacity of systems to reorganize and recover from change and disturbance without changing to other states ... systems that are “safe to fail” (p. 341).
Coaffee (2013) Social Science	“... the capacity to withstand and rebound from disruptive challenges ...” (p. 323).
Allenby and Fink (2000) Ecological, Social Science	“...capability of system to maintain its function and structure against internal and external changes and downgrade the performance of system when it must.”

Table 1.1 Definitions of Urban Resilience

The definition of resilience used through this research is that put forward by Meerow et al. (2016):

“Urban resilience refers to the ability of an urban system, and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales, to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform features that limit current or future adaptive capacity.”

Flooding and climate risk management literature generally incorporates risk assessment and the engineering interventions to lower and/or minimise risk. CI are essential drivers in any community’s recovery as urban societal continuity is heavily dependent on the availability of the functions provided by these systems during and after disaster events. Nevertheless, despite the barriers social and institutional factors present for successful disaster management, the question of which *management* actions should be taken to improve resilience has received comparatively less attention (Dieperink et al., 2016). Resilience theory enables the analysis of how communities and their CI systems can effectively prepare for and recover from natural disaster events. Engineering resilience as it has been applied to CI is based on the principles of returning the systems function to pre-disaster levels. When natural disasters destroy infrastructure, the economic losses are usually reported by reference to those direct costs or losses associated with the infrastructure itself. Resilience theory has led to the development of flood management tools and frameworks to minimise the impact of flooding and to maintain a functioning society.

Engineering sciences have a different outlook on resilience when compared to community resilience. To date the measurement of resilience has been based on engineering (technical) and community which has received comparatively minimal treatment in CI literature (social) spheres separately. Bruneau et al. (2003) proposed an engineering resilience framework with an emphasis on structural mitigation, especially the engineered systems concepts of robustness, redundancy, resourcefulness, and rapidity. The emphasis of engineering resilience is on building sound structures with an objective of: minimising any damage to CI; mitigating the consequences; and returning the CI to the pre-disaster state (Rose, 2007). In the event of a natural disaster event, these measures are useful for the protection of CI themselves, however, this operational

framework ignores the dynamic social nature of stakeholder communities and the process of enhancing and fostering resilience within and between communities.

Therefore a new approach is needed that is inclusive of non-technical elements, which are a relevant dimension for large-scale complex engineering systems. This research adopts a wider focus to examine how the resilience of CI systems relates to the functionality and well-being of the wider community, and views the combined system as a single socio-technical system (STS). Duit et al. (2010) suggest that an STS resilience perspective is also an approach for understanding how multilevel adaptive management can help society deal with complex problem clusters and cope with global change, while continuing to develop. The resilience of CI viewed as STS is therefore taking centre stage within the sustainability debate. This thesis offers a theoretical and practical contribution to the elucidation of a concept that is still relatively young to urban studies and therefore not yet sufficiently investigated.

1.2 Research Problem

The central problem addressed in this thesis is that traditional, risk-based, siloed systems of CI management are no longer adequate for dealing with the increasing complexity, dynamics and diversity of CI. Traditional risk analysis and risk management based on probabilistic quantitative methods have been widely adopted and have been useful for dealing with foreseeable and calculable stress situations. These traditional systems of management have struggled to deal with unprecedented global climate changes, increasing complexity of interactions, and the resulting uncertainties that challenge a transition towards resilience in Europe and specifically Ireland's urban regions. Traditional approaches based on risk management practices operate predominantly through hierarchical structures and processes, including top-down regulation. These management approaches are particularly prevalent in state institutions and public administration, which limit autonomy of agents at regional and local levels. While the Irish government have published policies towards the enhancement of system resilience, a new mode of STS-based management approaches is essential to respond effectively to the decision making challenges associated with climate disasters, including changing system dynamics and increased complexity.

The complexity and interdependency of STS presents a fundamental challenge to the most sophisticated risk analysis. Current policies and regulations rely on risk analysis based thresholds, however due to the rapidly evolving scale and cascading effects of natural disasters, risk-based approaches alone are no longer sufficient. New resilience management systems are needed to address the emerging issues associated with this complexity. Although engineering-based resilience research and development on methods and tools is progressing, establishing resilience measures which also include community resilience and related management tools is lacking. These tools are essential for the timely and broad acceptance of resilience concepts. An urgent need exists to complement the existing resilience knowledge base by further developing frameworks and models enabling STS-wide resilience analysis, engineering and management. The research explores the application of resilience concepts within existing resilience methodologies, with specific attention given to the interrelated area of risk management and risk assessment. Robust and implementable methods, including practices and measures for resilience management are established, in the form of a Resilience Management Framework (RMF). This will encompass risk based tools and methods for measuring and improving the resilience of STS that have capabilities for application across Ireland.

The defining property of STS is the alignment of interdependencies across levels, where agents must cooperate and build consensus in order to facilitate a transition towards resilience. The transition requires management approaches based on more sophisticated notions than the state actor as sole decision-making authority. Instead, new forms of management are needed that are based on autonomous actor networks and institutions that interact across scales and levels. These frameworks should provide actors at all levels of the STS with relevant information for them to make informed decisions (Holling 2001; Ghorbani et al., 2010).

The concept of resilience is discussed in further detail through the literature review in Chapter 2. Put simply, resilience is the capacity of an integrated STS - such as an ecosystem, human community or society, market or mixed economy, -to deal with change and continue to develop in a world facing many challenges and uncertainties (Huitric et al. 2009). STS resilience is a multifaceted and loosely organised cluster of concepts: abstract ideas or mental symbols that represent different aspects of an STS's

ability to persist, adapt and, when necessary, transform in continually changing conditions. Resilience provides a useful organising framework for the analysis of dynamics (e.g. the interplay between development, disturbance and renewal) of STS (Folke 2006; Walker and Salt 2006; Folke et al. 2010). Resilience and related concepts concerning persistence and change in STS have important implications for coastal EU cities in particular: the development and implementation of integrated urban management strategies for enhanced cooperation towards sustainable development of Europe's infrastructure systems. The RMF developed in Chapter 4 and caseed in Chapter 5 aims to measure and enhance the capacity of an STS to and deal with change in ways that sustain system functionality, adaptive capacity and the safety of local stakeholders.

1.3 Research Questions

Achieving effective urban resilience requires a paradigm shift in how CI is conceived of and managed towards Complex Adaptive System (CAS) thinking. There are significant and unaddressed challenges posed by global climate change regarding approaches to governance and management of STS. There is a knowledge gap between the theories informing the governance and management of CI and what is known about CAS. In other words, there is an apparent disconnect between the governmental approach to managing the impacts of climate change and a sound theoretical basis for them. Through this thesis, it is argued that the design of resilience strategies should be informed by *complex adaptive* STS (See Chapter 2). Furthermore, it is argued that STS-based governance and management is necessary if resilience is to be achieved in vulnerable urban environments.

1.3.1 Assumptions and propositions

In the early stages of this research initial propositions were developed as a foundation on which the resilience theory could be developed. These propositions were provisional and intentionally designed to aid the exploration of the research topic. The propositions provide a starting point for the research, from which an understanding of STS-based resilience could be developed. As the research developed and the gathering of information led to a greater understanding of the topic and knowledge was built up, it led to the revision and refining of the propositions as the research progressed. The

primary underlying proposition is that a resilience based management framework can achieve long term sustainability of STS.

Deconstruction of this proposition led to a set of normative assumptions that underpin this research:

Assumption 1: Urban resilience in Europe CI is both possible and desirable.

Assumption 2: It is possible to design an STS-based framework for integrated urban management and governance.

Assumption 3: It is possible to identify and describe key attributes of STS, including resilience, at the macro-regional level.

These assumptions led to an initial set of propositions, which provided a point of departure for the study:

Proposition 1: The related STS properties of resilience, adaptability and transformability determine the possible sustainable development trajectories and future identities of urban STS.

Proposition 2: An urban STS that encompasses Dublin water management system is conceivable.

Proposition 3: The Dublin water management system is an appropriate unit of analysis with which to explore the concepts of STS resilience management and governance architecture in relation to urban regional sustainability.

1.3.2 Research Questions

The research questions (RQ) were formulated to guide the resilience research process in general and the study of STS in particular. RQ 1, 2 and 3 were formulated in the context of the central research question and on the basis of an initial review of the literature, informal discussions with colleagues working on resilience and infrastructure projects, and the propositions outlined above. RQ4 was added during the course of the study to provide additional clarity on the practical application of the framework developed. In addressing the research problem outlined above, the following research questions were developed and these will be addressed through the research:

RQ1. How are resilience analysis strategies currently being employed in conjunction with STS?

RQ2. How can the resilience of STS be determined?

RQ3. How can STS be managed to reduce physical, social and economic vulnerability to multiple hazards, increase capacity to tolerate and deal with change, and so achieve regional urban resilience?

RQ4. Can a holistic resilience framework for the assessment of STS be developed and operationalised?

1.3.3 Aims and objectives

Through this research the concept of resilience is applied to STS. It provides a lens through which to study and understand socio–technical relations and sustainable development of the system during instances of disturbance (Folke, 2006). The aim of this research is to develop an understanding of the conditions enabling the long-term resilience of STS. It does so from a theoretical and an empirical standpoint. Thus its aim is twofold: to contribute to the urban resilience field by bringing clarity to this concept that over the last decade has been extensively used, albeit interpreted in different ways; and to develop and test management approaches to embed resilience within STS design processes.

The main objective of this study is to develop an urban resilience measurement and management framework for STS. This framework also considers wider governance issues facing the retrofitting of resilience tools on traditional risk management approaches. The central research question asks whether it is possible to achieve this insight by using an STS as a conceptual framework and analytical tool to relate management to resilience and development.

Within this overall aim the specific objectives of the research are:

- To research and document how the notion of resilience is interpreted and perceived by expert stakeholders in STS;
- To test the proposed framework and its associated tools through a case study to assess the efficacy of the assessment framework for the purpose of identifying and improving the conditions for resilience in the STS;

- To identify advantages and shortfalls of the assessment framework as well as its potential to improve upon current assessment tools with regard to long-term planning.

1.4 Employment Based Research

A major influence on this research is the funding and programme design which facilitated it to begin with. This research was funded under the Irish Research Council Employment-Based Research Programme, which provided the researcher with the opportunity to work with industry partners on live research projects while carrying out his individual research. In particular, the researcher was heavily influenced by his work on the EU H2020 project RESILENS (Realising European Resilience for Critical Infrastructure) <http://resilens.eu/>. The RESILENS methodology is designed to facilitate the delivery of improved resilience for CI systems. The considerable time spent working on this project with leading academics and industry partners in the resilience field influenced the initial research approach. The project literature review, related research and discussion with European resilience experts carried out as part of the RESILENS project informed the tool design and methods used here.

The researcher's role as a participant in the RESILENS project formed the foundation of his understanding of resilience and approaches to tool development. Through the literature review papers relating to the development of resilience over time and the application of urban resilience to STS were sought. The review also aimed to assess the alignment between the literature and the RESILENS project approach. Moreover, as the initial aim of the research was to produce research of interest for CI service providers, it was decided that a case study approach would be most fitting to produce feasibility testing and working demonstrations of the work, which could be readily translated to live cases in the field. The case study research would be reviewed and the final results would necessarily be corroborated through an interview process with industry leaders, public managers, and academic experts.

The research began with the idea to conceptualise the RMF as both an analytical construct representing the greater Dublin area as a macro-region and the unit of analysis for understanding governance architecture for urban resilience management in Ireland.

This was underpinned by the work on the RESILENS project. The envisaged study would involve both deductive reasoning proceeding from general principles to understand the Dublin case and inductive reasoning that derives broader generalisations about STS from observations about Dublin. The study would develop and use a conceptual RMF consisting of key resilience concepts and other components of complex adaptive STS theory to guide the analysis of infrastructure systems and the communities that they support in Dublin.

In addition to researching the various partner options and building a relationship with the managers the selection of which companies would be the best fit with the research was influenced by the critical realist perspective. The objectives and outputs of the work on the RESILENS project and the flood sensor work in VT-IoT were practical and but could also be critically reviewed by many of the work and project partners which would better ensure their validity. See section 3.2.2 for the Methodological Perspective.

1.5 Structure of the thesis

This thesis is divided into seven chapters that address five main themes: (1) urban resilience development (2) complex adaptive STS theory (3) the multifaceted concept of STS resilience and STS-based governance and management framework, which are needed for shaping (4) a transition towards resilience using insight based on analysis of (5) an urban STS conceptualised as the Dublin water management system. The structure of the thesis is shown in Figure 1.1.

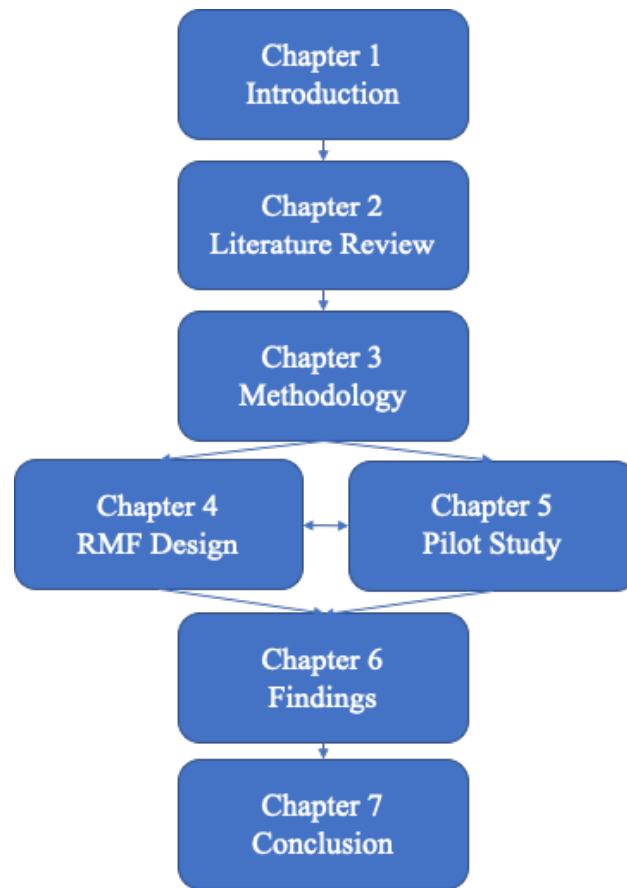


Figure 1.1 Thesis Structure

Following this introductory chapter, Chapter 2 presents the findings of the literature review contextualising the research problem and presenting a justification for the study of the STS resilience. It describes the general research background in terms of the urban resilience context and the management approach to enhance STS resilience. The chapter considers key elements of STS for resilience management and governance.

Chapter 3 describes the research framework for addressing the research problem and questions identified in Chapter 1. It charts the researcher's philosophical stance and methodological perspective, which underlie the research approach, design and methodology used to address the research questions. The chapter justifies the analysis of STS and explains the mixed methods research strategy adopted for the study of the water management system in Dublin. It also describes the methods used in the research.

Chapter 4 presents some general design guidelines for STS-based management and details the theoretical basis of each of the six stages of the RMF. It describes the logic

and design process for the selection certain tools and how they combine to deliver an understanding of the STS, a resilience score and how to improve the resilience of the system both prior to and after a disaster event.

Chapter 5 details the case testing of the RMF and its application to the Dublin water management system. The conceptualisation of the Dublin water management system is the unit of analysis for understanding STS in general. This chapter highlights the benefits and issues of introducing new technologies (in this case smart sensors) to STS as part of the proposed RMF.

Chapter 6 presents the findings of the case study and the expert interviews. It describes the study results and analysis regarding key characteristics: boundaries and boundary conditions; system structures, processes and functions; structural hierarchical relationships and cross-scale interactions between the water management system and other CI; human activities, disturbances and other drivers of change that affect the resilience of STS.

Finally, Chapter 7 draws on the insights from the previous chapters, links concepts, and draws together insights to answer the research questions and arrive at a number of conclusions. This chapter summarises the main themes and issues, identifies the limitations of the research, reflects on the contributions of the research to the urban resilience field, and presents recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

In order to achieve the objectives outlined in Chapter 1 the first step is to analyze the relevant literature and build a foundation of knowledge with which to develop a framework suitable for the management of urban resilience. To begin, this chapter reviews approaches to critical infrastructure (CI) management and the issues around the complex interdependencies between systems. The evolution of resilience theory is detailed from its introduction in ecology, followed by its application in engineering and community resilience. A number of approaches to resilience measurement were reviewed and the description of several resilience models were highlighted. Further advancements are proposed to incorporate community resilience and CI resilience in a single resilience framework by viewing the urban environment as a series of interrelated socio technical systems (STS). This Chapter highlights the ongoing transition from a more traditional approach to CI protection which is siloed in nature to the more holistic approach of STS resilience. The later sections of this Chapter attempt to explain this shift from critical infrastructure protection (CIP) to STS resilience.

Figure 2.1 below visualises the links between the different research areas and the development of resilience.

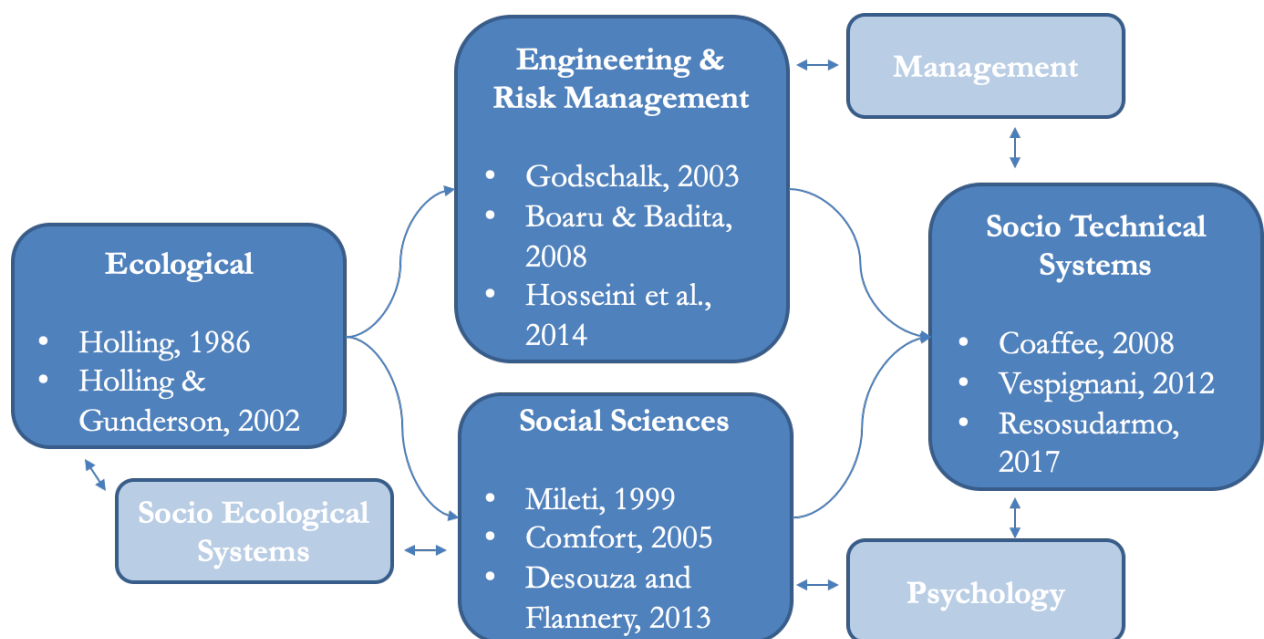


Figure 2.1 Resilience influences across research areas and major works

In Chapter 4 the six stages of the Resilience Management Framework (RMF) are developed. The aspects of the literature review which formed the basis of these stages are also highlighted here.

2.1 Introduction

As the global population continues to experience rapid growth there is a mounting strain on the urban environments servicing these populations. There is an immediate need to provide a safe built environment in the face of both the foreseen and unforeseen impacts of natural and manmade hazards including climate change and terrorist attacks. The resilience perspective related to this challenge needs to be rooted in spatial planning for more resilient infrastructure networks and their improved resilience (Boin and McConnell, 2007). This will be achieved through management solutions, accurate allocation of funding, creative policy and redundancy planning. With the main goal of urban resilience research generally targeted at guaranteeing the social and economic keystones of modern societies, a logical starting point for the analysis of resilience is to focus on STS or organisations whose functions are deemed essential for societies to function (Pursiainen, 2018). This chapter describes urban resilience theory and addresses how it can be applied to complex STS.

This chapter reviews the development of resilience over time, its application in different contexts from ecology, engineering, community and urban resilience, and the analysis approaches currently in use. As detailed in Chapter 1 the main objective of this research is to explore the feasibility of urban resilience measurement and the potential use of resilience management tools for use in STS. Furthermore the basis for a framework for the analysis and management of resilience in urban environments is developed. This chapter reviews the development of the resilience concept from its initial use in ecology to its application in communities and CI. Finally the chapter reviews how resilience has been applied to STS and the various analysis methods currently in use.

2.2 Coping with Complexity

In the wake of the world trade centre attacks on 9/11, CIP became a buzzword in the US and was adopted quickly in the European Union (EU) (Lewis, 2014). This culminated in the development of the European Programme for Critical Infrastructure

Protection and its corresponding legislation. CI are defined by the EU Council Directive as: *‘A system or part thereof which is essential for the maintenance of vital societal functions, health, safety, security, economic or social wellbeing of people and the disruption or destruction of which would have a significant impact on society as a result of the failure to maintain those functions’* (EU, 2008).

The term ‘critical infrastructure’ has been extensively mentioned and explored in a wide variety of research disciplines ranging from environmental science and ecology, engineering, computer science, social sciences, operations research and management science, and risk management (Gopalakrishnan and Peeta, 2010; Bessani et al., 2008; Dunn, 2005; Xu, 2012; Brown et al., 2006; Moteff, 2005). A Web of Science database assessment of academic publications (1986-2016) identified over 2440 peer reviewed papers from different research domains explicitly focused on, or which addressed, certain aspects of CI related research. There exists a plethora of topics such as CI risk assessment models (i.e. Moini, 2015; Rodriguez et al, 2015), propositions of frameworks, methods and tools to facilitate CI resilience (i.e. Hosseini et al, 2016; Bochkov et al, 2015), and an evaluation of CI interdependencies (Emery & Schulman, 2015, van der Vleuten et al, 2013; Wu et al, 2016).

As noted in the definition above CIs have been acknowledged as playing a central role in the functioning of society and continued safety of its citizens (EU Council Directive, 2008). CIs include the systems that support services encompassing areas including transportation, energy, communications and water provision. As technology has advanced CI systems have grown in size with enhanced complexity and overlapping between systems. This has had the result of increasing risk and possible disruption (O’Rourke, 2007). In addition, rapidly changing technology can create points of weakness in CI systems which despite their importance are often not updated with any regularity (Coaffee and Fussey, 2015). More traditional risk assessment approaches have been unable to provide adequate analysis of systems weakness for cyber risks which are not quantifiable using traditional methods (DiMase et al., 2015). CI systems may be viewed as non-linear, dynamic complex systems; a system is resilient when it can adapt and recover in the event of disaster (Coaffee, 2008).

The built environment can protect against short-term climate shocks and long-term gradual climate changes (Hamin and Gurran, 2009). CI with this potential include energy, transportation, water management, transportation and communication infrastructure. Much of the analysis of resilience in these systems focuses on their capacity to withstand or recover from the effects of rapid onset climate events (Linnenluecke et al., 2012). Such strategies often include establishment or improvement of standards and codes, construction of barriers or other added infrastructure. In longer-term adaptation decisions, an emphasis on climate proofing infrastructure has increased in the development community. Climate proofing can sometimes mean merely adding building material or strengthening an existing project along the margins, however where these improvements are made is often made on a subjective basis. Innovative long-term planning and climate proofing includes consideration of more forward-looking adaptation options such as relocation or redesigning infrastructure decisions beginning with their core assets.

CI systems may be viewed as a composite series of assets. Only some of these assets are central or ‘core’ to the functionality of the system as a whole. In 2003, the Homeland Security Presidential Directive was explicit in the need for the prioritisation of the core assets within designated CI systems. This was deemed to be highly important in the overall strategy implementation. The strategy states; ‘the assets, functions and systems within each critical infrastructure sector are not equally important. The transportation sector is vital, but not every bridge is critical to the nation as a whole.’ Through this research, a core asset is defined as an essential, important or valuable property of a CI without which the owner cannot continue the provision of functionality and profit-making activities. However through the review of the studies presenting a methodical basis for designating selected systems and parts thereof as ‘critical’ was observed to be lacking (Frost et al., 2000). This literature influenced the design of Stage 1 of the RMF ‘Selection of essential organisational components’, for further details see section 4.4.

2.3 Defining Resilience

In his seminal 1973 article, C.S. Holling first applied the term resilience to ecological systems, his definition of resilience is the ability of systems to ‘bounce back’, manage

crisis, and to endure under stress. He suggested that in addition to ‘stability’ ‘[...] *there is another property, termed resilience, that is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables*’ (Holling, 1973). Holling developed the adaptive cycle which suggests that systems alternate between long periods of aggregation and transformation of resources and shorter periods that create opportunities for innovation. This cycle underpins many of our current resilience applications and is proposed as a fundamental unit for understanding complex systems from cells to ecosystems and societies. Figure 2.1 below demonstrates the four phases of the cycle: growth or exploitation (r), conservation (K), collapse or release (Ω omega), and reorganization (α alpha).

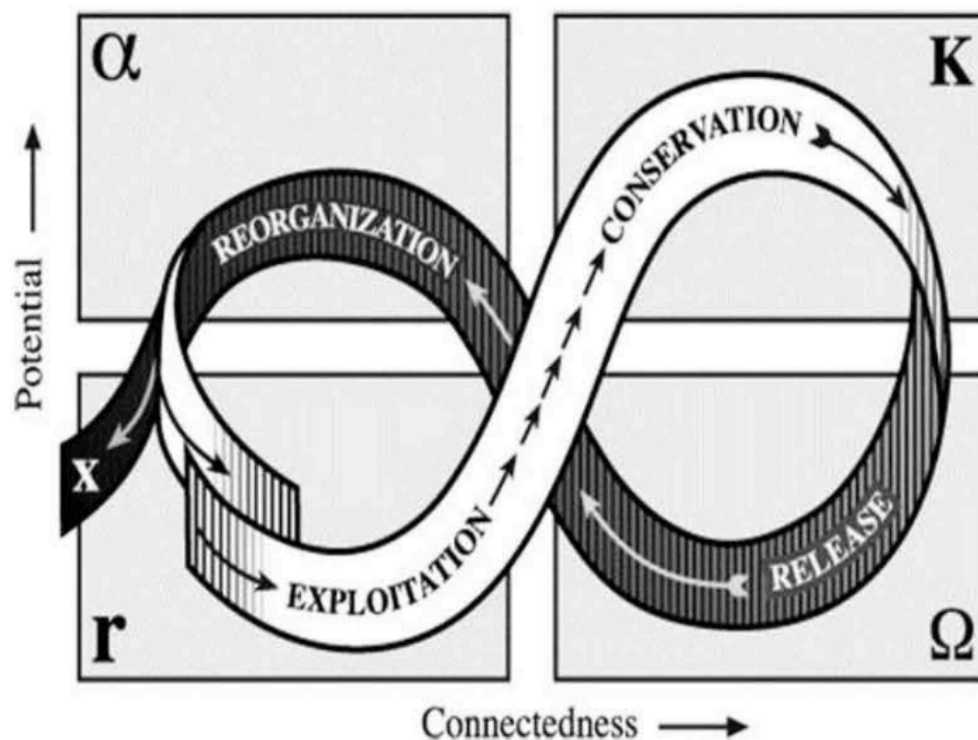


Figure 2.2 The adaptive cycle (Holling and Gunderson, 2002).

As a system grows from the exploitation phase (r) to the conservation stage (k) resources are slowly acquired. This phase is known as the fore-loop as seen on the Figure 2.1 and shows the system increasing in potential on the Y axis. This increase in resources leads to an increase in fixed connections (or connectedness on the X axis) which reduces flexibility making the system more brittle and unable to respond. If the

system is too brittle it will be incapable of responding to external or internal disruptions which will increase the likelihood of a system collapse or release (Ω).

In contrast to the fore-loop the 'back-loop' of the adaptive cycle shows the system reducing its connectedness and once again increasing the potential. This phase is often fast moving and may occur in a short time period. Due to the collapse of rigid structures during the release phase the system now has an opportunity to redistribute its resources, and establish new structures. During this reorganisation (α) stage the system may be quite chaotic. This chaos increases the opportunities for the likelihood of creative change.

At this stage the system may undergo a regime shift illustrated by the 'tail' (x) in the figure. Alternatively the changes introduced in the reorganisation phase are tested and may begin to redefine the characteristics of the transformed system. The process repeats itself as the redefined characteristics are embedded and themselves become rigid overtime,

Through his research, Holling (1996) further defined the phrase 'engineering resilience' to identify the difference between maintaining system equilibrium and ecological resilience which is more concerned with the continuity of the system without necessarily returning to the previous equilibrium. Ecological resilience and engineering resilience are not incompatible. Walker et al. (2004) suggest that engineering resilience only provides part of the picture and that it fails to provide a complete resilience measure of a system. Holling and Gunderson (2002) identified links between resilience and adaptive equilibrium models. The adaptive cycle which was originally developed from ecology was later applied to other research fields including engineering, business and economics (Zolli and Healey, 2012). Holling's engineering resilience concept has been adapted and has been combined with risk analysis and management techniques which aim to maintain economic functioning in turbulent markets enabling systems to endure under stress (Beilin and Wilkinson, 2015).

Engineering resilience as defined by Holling may be viewed as the precursor to urban resilience as it is used today. Due to the high levels of connectivity within urban systems, even localised events such as coastal flooding, disease outbreaks, political

unrest, or economic disturbances can have major impacts on the wider system. Coaffee (2013) explains how resilience has proliferated as a policy metaphor for adaptability. His paper supports the theory that population density, local infrastructure, social structure and economic flows, can contribute to greater resilience, or may worsen vulnerabilities. Urban planning, governance, and management for resilience are important factors in supporting continuity goals for infrastructure systems (McPhearson, 2014).

Although the fields and systems where they are applied may change, the aim of returning to a previous equilibrium remains the primary aim in the majority of sustainability and urban resilience literature (Folke, 2006). More recently, the concept of resilience has proliferated as a policy metaphor for embedding ‘foresight’, robustness and adaptability into a variety of place-making and increasingly local planning activities (Coaffee, 2013); particularly as cities are increasingly seen to amplify global urban trends of enhanced risk (Simpson and Stoffregen, 2011).

While each new adaptation of resilience maintains the same aim of returning to equilibrium, the application in the social sciences is complicated by the difficulty in analysing many individual actors in each system. Furthermore, the process of attempting to increase resilience for unforeseeable change is different from attempting to improve system performance during times of stability and growth, as exemplified by a decision analysis approach (Park et al., 2013). Both approaches are necessary to improve the sustainability of the system in the long term but, to date, the emphasis has been more growth focused. In decision analysis, possible policies are evaluated using the probability distribution of system trajectories that each candidate policy generates. The decision analysis process identifies the policy that maximizes expected utility, or minimizes expected losses (Geels et al., 2017).

From Holling’s initial use of resilience in ecology the concept has transferred well to the hard sciences of physics and engineering, however as resilience continues to be used in more complex social situations a number of issues have arisen (White and O’Hare, 2014). The greater complexity of the system reduces the ease of application of previously developed resilience theories to be applied appropriately in social cases. Resilience has *‘evolved through the application of ecological concepts to society*

assuming that ecological and social system dynamics are essentially similar' (Brown, 2013), however resilience theories have developed in *'remarkable isolation from critical social science literature'* (Cote and Nightingale, 2012). Ecological and social system dynamics are not directly transferable and the issue of agent autonomy in social systems is highlighted in Section 2.5.

Engineering resilience refers to technical systems designed by engineers such as CI which interact with humans and physical assets, such as energy, water, and transport systems. Hollnagel (2009) explains that the core aim of engineering resilience is to understand normal system functionality and how it fails. Economic resilience is defined as *'the inherent ability and adaptive response that enables systems and regions to avoid maximum potential losses.'* In the event of a disaster this translates as adaptation and restoration of the system structure to ensure continued growth of output (Rose, 2004).

The development of resilience across various different fields of research has complicated its application for the complex adaptive systems found in the social science literature (Carpenter et al., 2004). There are several definitions currently in use and these do not always lend themselves naturally to the development of consistent resilience metrics (Hosseini et al., 2016). Through his research Ayyub (2014) establishes the importance of enhancing system resilience of structures, networks, and communities. He defines systems resilience as: *'The potential of a particular configuration of a system to maintain its structure and function in the face of disturbance, and the ability of the system to reorganize following disturbance-driven change.'* Simme and Martin (2010) put forward a number of resilience uses in evolutionary economics where the adaptive cycle has been adapted to the urban environment to embrace bounce-back approaches. As resilience has developed the increasing number of definitions have led to a loss of meaning. Therefore, rather than proposing yet another definition of urban resilience for this thesis, the definition suggested by Meerow (et al. 2016, p. 45) has been adopted through this thesis.

"Urban resilience refers to the ability of an urban system, and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales, to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to

change, and to quickly transform features that limit current or future adaptive capacity.” Meerow et al. 2016.

This definition offers a number of pathways to achieve resilience through persistence, transition and transformation (Meerow et al., 2016).

- Firstly, it moves away from the central concern of returning to a state of equilibrium, as detailed above the concept of a resilience equilibrium stems from the engineering perspective where a system in equilibrium is disturbed by external forces and should aim to return to the original state. This definition highlights that the system functions should be maintained but that due to the outcome of changes, the system may not be to return precisely to the previous equilibrium.
- Secondly, although resilience is primarily concerned with adaptation in the event of a disturbance, this definition discerns that disturbances and responses will vary in different contexts.

These characteristics are particularly advantageous for the application to socio-technical systems (STS) which are explored in Section 2.5. For example, a socio-technical system may be resilient to flooding but may still be vulnerable to a terrorist attack. It is important to acknowledge the type of system, the type of impact, and the normative perspective of the agents involved). Acknowledging the importance of context when discussing resilience has complicated efforts to design single general measures of resilience across time and systems.

2.4 Community Resilience

Mileti (1999) first adapted the resilience concept and applied it to communities and their capability to recover from natural disasters. He suggested that community resilience is the community’s ability to recover from disaster using its own resources. Through his research Mileti worked to create more resilient communities, he carried out analyses on many aspects of resilience and how they responded to various hazards. The definition he put forward has remained popular with subtle adaptations including research by Norris et al. (2008) where community resilience is described as the community’s ability to respond and change after adverse events which included social

capital and economic development among other adaptive capacities. Norris differed from Mileti (1999) in that although mitigation is cost effective for disaster events he suggests that it remains distinct from resilience (Rose et al., 2007). Paton (2000) suggested that community resilience is the ability of the community to bounce back and to use its physical and economic resources effectively to aid recovery following exposure to hazards. Ganor (2003) highlighted the ability of individuals and communities to deal with a state of continuous, long term stress; the ability to find unknown inner strengths and resources in order to cope effectively; the measure of adaptation and flexibility. These two views appear to merge to with the definition put forward by Norris et al. (2008) that community resilience should be concerned with the individual's sense of the ability of their own community to deal successfully with the on-going political violence, which is comprised of the material, physical, socio-political, socio-cultural, and psychological resources that promote safety of residents and buffer adversity.

Adger (2000) and Norris et al. (2008) developed the ecological definition of resilience to encompass all human communities. Their focus on community led to the development of social measures including local demographics, resource and economic dependence, and the strength of various institutions in the community. Community resilience is related to the vulnerability of the community to disasters (Cutter et al., 2003). Natural disasters expose the vulnerabilities of communities and Pelling (2003) outlines that exposure, resistance and resilience are needed to recover. Resilience is normally seen as the opposite to vulnerability, however some researchers view the two concepts as being interrelated (Gallopini, 2006).

It is clear that different social groups have widely varying levels of resilience. Different groups and individuals have socially differentiated capacities which depend on the levels of poverty, age, gender, and ethnicity, which all contribute to community vulnerability to climate change hazards such as flooding. These capacities may be enhanced through quality of housing, their location, and the access to STS (Moser and Satterthwaite 2010). Satterthwaite et al. (2009) outline the need for individuals and their assets to be considered as resources which may be used by the community in the event of a disaster. These resources may include financial, physical, natural, or social assets (Moser, 2006). First responders, local government and community services are the key

planning organisations within community resilience and are rarely considered in engineering resilience design (Satterthwaite et al., 2009). The capacity of the STS to assess these assets in order to improve resilience includes the collective effort of these actors and services (Berkes, 2007).

Policy makers in Ireland and across the EU have adopted resilience as a dominant theme in their approaches to improve community safety from climate related events. The use of resilience at high levels of EU policy making sets a clear policy goal; communities that invest in resilience and CI will be in a position to withstand the effects of natural disasters then would be the case if no investment was made. In December 2016 the department for Transport, Tourism and Sport, published, a framework to develop a Climate Change Adaptation approach to improve the resilience of the transport sector in Ireland. Climate Change Adaptation refers to how the Irish Government plans to address the negative effects of climate change and the suitable actions it should take to prevent or minimise damage caused. The transport adaptation plan was prepared as part of the National Climate Change Adaptation Framework (DCCAE, 2012) developed by the Environmental Protection Agency (EPA) in line with EU guidelines, as well as the provisions of the Climate Action and Low Carbon Development Act 2015. Stemming from the EU policy there has been a notable investment in research in resilience of CI including the Turas, SmartResilience, and Realising European Resilience for Critical Infrastructure (RESILENS) research projects in which Irish research institutes are involved. These projects provided a blueprint for defining and fostering disaster resilient communities and stimulating the initial interest in disaster resilience. We will be drawing on these projects as part of this research.

Although resilience has been and is being promoted by the policy community there remains hesitance within the research community with regards to the acceptance and application of the concept for community disaster impacts. The cause of this hesitance appears to stem from a focus on the number of varying definitions of resilience, the use of ‘resilience’ across different research fields from engineering, ecology, economics, and sociology, and whether resilience can be viewed as a transformative process or is in itself an end result (Cutter, 2008; Kahan et al., 2009; Klein et al., 2003; Manyena, 2006; Norris et al., 2008; Rose, 2007).

Information and communication become vital in emergencies for key actors and the wider public (Head, 2008). Key actors within the STS should be aware of information around potential threats, disaster plans, and resilience measures to mitigate negative impacts in a disaster event. These actors can then communicate the risks and their recommended course of action to the public and other stakeholders effectively. In the event of an emergency there is limited time for information checks and debate around decisions, the source of the information should be trustworthy and known to the recipient where possible (Longstaff, 2005). A wide array of communication pathways such as radio updates, websites, phone hotlines or SMS notifications are valuable resources in times of emergency. While communication is key to keeping stakeholders informed prior to a disaster event the communication capacity can be increased in the event of a disaster to coordinate and deploy resources (Norris et al., 2008).

At risk communities must be aware of their options and be come together to work flexibly to solve problems. In terms of improving overall resilience, information is the primary resource to enhance communities' adaptive performance (Comfort, 2005). Individuals throughout the community require a common understanding of the threats and resilience management plans in order to improve the overall community resilience (Ganor and Ben-Lavy, 2003). Disaster plans rarely foresee every possible outcome and so the key to solving emerging problems is the capacity to acquire trusted and accurate information (Longstaff, 2005). This literature influenced the design of Stage 1 of the RMF 'Building resilience awareness', for further details see section 4.3.

A community's resources dictate its adaptive capacity; more resilient resources have dynamic attributes such as robustness, redundancy and deployment rapidity (Armitage, 2005). Resources are not static and evolve as time progresses. The impact of disasters on community resources and how these resources can negate disaster damage the network is a point of debate in the literature, the adaptive capacities that result in community resilience are not a singular condition which may be measured or monitored simply. It is a set of resources with many dynamic attributes and transactional linkages and relationships. Moreover, social, economic, and physical or technical forces operating at higher system levels undoubtedly influence these capacities that operate at the community level. These capacities may be observed using a mixture of quantitative and qualitative methodologies, the various factors that influence or reflect community

resilience may be measured using frameworks and or resilience indicators (Bruneau et al. 2003; Rose, 2004). Resilience measurement approaches are explored further in section 2.6 below.

2.5 STS Resilience

This thesis adopts urban resilience research and seeks to apply it to STS. STS theory views the social systems that support services encompassing areas including transportation, energy, communications and water provision as a single system. STS are non-linear, dynamic complex systems; as technology has advanced STS have grown in size with enhanced complexity and overlapping between systems (Ropohl, 1999). This Section explains why urban systems (CI) maybe understood and studied as ‘socio-technical systems’.

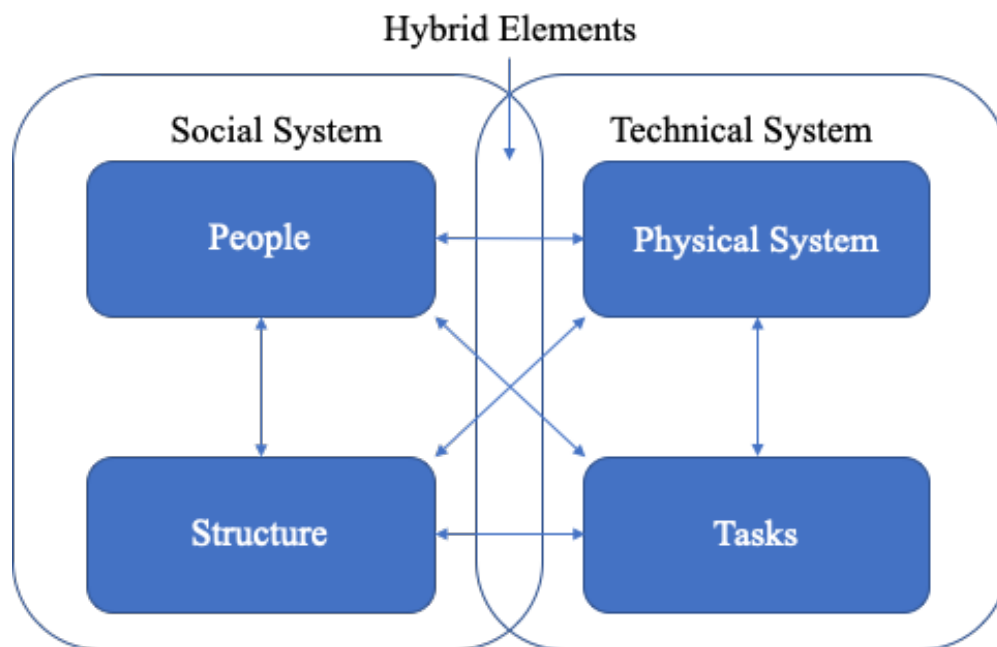


Figure 2.3 STS intersecting sets model (Oosthuizen and Pretorius, 2016)

A hybrid perspective allows us to conceptualise socio-technical relations in terms of constructing an STS. An STS can be defined qualitatively and represented in terms of either a network or intersecting sets. The socio-technical network consists of social, technical and hybrid elements and their relationships. The intersecting sets model is composed of two sets of elements – one technical and the other social. The hybrid domain is represented by the intersection of the two sets (Becker, 2012). The advantage

of the network model is that it represents the relationships between elements, whereas the intersecting sets model does not. The advantage of the latter is that it represents functional boundaries clearly and enables the identification of important relationships, interactions and interdependencies with other systems (Mohaghegh et al., 2009).

In his seminal paper, Trist (1981) explains that when it was first conceptualised, the STS paradigm entailed a shift in the way work organisation was envisaged. Further, Smith and Stirling (2010) identified that technology-focused literature on socio-technical transitions shares some of the complex systems sensibilities of social-ecological systems research. It is important to note that although some of the literature on CI resilience does not specifically mention STS, through this research CI have been identified here as STS.

STS are complex by nature; however, the analysis of these systems is often carried out in a linear fashion. Current assessment models assume that supporting systems will continue operating regardless of any disaster event. This assumption effectively decouples the system from its supporting infrastructures and focuses on the dependencies rather than on the interdependencies of the STS in question. A clear understanding of relationship between systems and how they interact is needed to avoid disastrous results and is therefore vital in the analysis of the interdependency between infrastructure systems (Boaru & Badita, 2008).

Socio technical theory deals with hybrid constructions (epistemic objects) such as STS, which are the fundamental objects of curiosity and research (Bostrom and Heinen, 1977). Socio-technical research investigates organised clusters of social-technical problems in a holistic and systemic way. It analyses the complex and dynamic patterns of relationships among people, society and the physical systems they work with, as well as the possibility of their transformation (Vespignani, 2012). It addresses continually changing socio-technical realities, which are often contradictory due to the plurality of perspectives involved. Socio-technical research is also normatively concerned with producing useful knowledge; that is, knowledge for solving complex social problems and informing decision making regarding resilience and resilience development (Trist, 1981).

The urban environment can be viewed as a set of nested and overlapping complex adaptive STS and these may be viewed as a type of CAS. This literature adds dynamics which may not be as clearly defined in the STS literature. Systems may vary in scale across time (Levin et al., 2013). According to Mumford (2006) integrated studies of human and technical systems reveal new and complex patterns and processes not evident when studied separately. Properties of Complex Adaptive System (CAS) present in STS are the feedback loops, non-linear dynamics, legacy effect and time lags (Kim and Kaplan, 2006). Further STS benefit from collaborative decision making and the emergence of agents who play an important role in the systems continued success (Rhodes and Murray, 2007). Improving the resilience of the system is not necessarily the same as improving the systems output but a complexity friendly resilience performance management will increase the adaptive capacity of the STS under its purview. In doing so, the STS can produce better outcomes for those it is seeking to support (Lowe et al., 2016).

A system is resilient when it can adapt and recover in the event of disaster (Coaffee, 2008). A resilience management structure must consider the STS in its entirety. Often these systems of systems, involve numerous governing bodies which have isolated decision making processes. The STS includes its geographical boundary area, contextual boundary, and the dynamic relationships between the different levels of the STS (Djalante et al., 2011). In 1993, Kooiman put forward the interactive governance approach which suggests that the processes of governing socio-political systems occur in the interactions between multiple actors across multiple levels of the system.

Following EU structural reforms in 1988, multi-level governance was first used to capture the developments in structural policy, this has since been applied more widely to EU decision making (Marks et al., 1996). The definition of governance used through this research was put forward by Benz (2006): ‘political structures and processes that transgress the borders of administrative jurisdictions, aiming to cope with interdependencies in societal development and political decision-making which exist among territorial units’. The multi-level governance concept thus contained both vertical and horizontal dimensions. ‘Multi-level’ referred to the increased interdependence of governments operating at different territorial levels, while

‘governance’ signalled the growing interdependence between governments and nongovernmental actors at various territorial levels.

The multi-level governance approach has more recently been applied to low carbon transitions for STS (Geels, 2012). It draws on domestic and international approaches to politics scholars found the need for analysis across increasingly contested jurisdictional and territorial boundaries both within and beyond states (Pierre and Stoker, 2000). Here governance architecture is based on the three components of the STS itself, the governing system and the interactions between the two (Weyer et al., 2015). The interactions between the STS and the governing system reflect the diverse dynamics and complexity of the underlying context. This is particularly important for resilience as actors at different levels across the system must work together to enact system responses especially at a time of crisis.

Resilience provides an analytical lens for examining the complex relationships and dynamic interactions between our societies, economies, and CI (Leveson et al., 2006). Resilience management and STS are two widely recognised management design strategies. The multifaceted concept of resilience management provides the kernel of the STS approach to resilience research and practice. While both approaches advocate a degree of technical proficiency, to date research has not been investigated where potential crossover and synergies can be gained from combining these two management approaches. This research addresses how these approaches may be combined to achieve flexibility and stability with the urban environment. This section looks at how an STS perspective can inform urban resilience research.

A key to developing resilience in STS is the integration between top-down planning and bottom-up demands particularly in the post disaster reconstruction phase. Ignorance of the local cultural context and site-specific resilience may result in initiatives which do not reflect the cities’ actual demand for development and cannot be considered sustainable. Developing urban resilience of a post-disaster STS calls for socio-spatial coherence in the urban plans and projects, and interdisciplinary and multi-stakeholder integration and communication (Guo, 2012). Therefore reconstruction plans should be flexible so they may be applied to case specific contexts inclusive of local dynamics, agents and available resources. Consideration should also be given to the scales at

which reconstruction is taking place, the social and spatial changes which may influence the capacity to deal with future disasters, and the current tools and approaches in use in the STS (Amaratunga and Haigh, 2011).

In many cases, it is impossible for an individual to have a sufficient understanding of the entire STS by simply synthesising separate analyses of the various economic, societal or infrastructure components contained within. STS are irreducible due to their complexity and must therefore be investigated as a whole (Righi and Saurin, 2015). Resilience provides an organising framework for understanding the complex adaptive dynamics of STS. In the event of a disaster the reorganisation of the STS will take place across the social and technical domains but also across the internal spatial scales. Resilience thinking addresses the non-linear dynamics involved in this reorganisation both prior to and in the wake of a disaster. Tewdwr-Jones (2017) highlights that governance of CAS such as STS must take into account the inherent interactions and interdependencies between levels. Adaptive governance is aimed at integrating resilience decision making which manages for change rather than against change (Ahern, 2011). Lowe et al. (2016) explain that rather than making agents accountable for their results to their superiors at higher STS levels, accountability should be rethought so that rather than being ‘accountable’, agents should ‘provide an account’ for their decisions to their peers.

Gallopín (2006) points out that resilience can operate at different levels and scales, reflecting different types of system stability: the level of local stability or engineering resilience; the intermediate level of changes between multiple stable states or resilience; and the level of changes to the entire stability landscape. At each of these levels social relations between actors will dictate the success of resilience framework. These agents are organised across different institutional settings, in different cultures and with different power relationships at play. There may also be significant differentials between autonomy which may impact on the time to react in the event of a disaster. The levels across the STS are demonstrated in Figure 2.1.

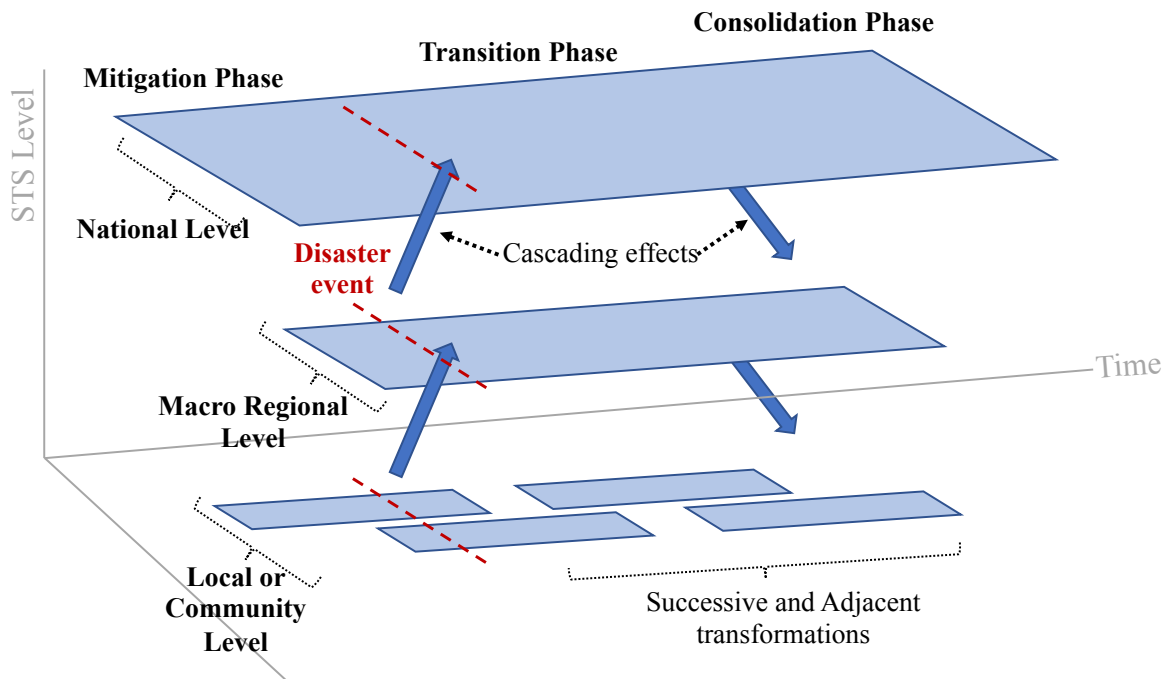


Figure 2.4 STS Levels

Complex systems are inherently difficult to conceptualise and describe. Describing society–technical relations in terms of integrated STS is an ontological and epistemological challenge. Furthermore, the analysis of STS is a paradox because the construction of such an integrated unit of analysis begins with an essential distinction between human society/culture and nature (Geels, 2005).

Asset based adaptation demonstrates how urban communities can increase the level of their resilience by organising their assets using preventative risk reduction strategies through collaboration with local governments (Moser and Satterthwaite, 2010). This also considers the necessity of the community to both organise their own assets, and to coordinate with neighbouring communities and local government for disaster preparedness to improve resilience (UNISDR, 2012). Gunderson and Holling (2002) together with Twigg (2007) summarise these agent and asset capacities as follows:

- (i) Responsiveness; is the capacity of a flexible community to plan and prepare for disaster events and then to respond quickly when they occur;
- (ii) Resourcefulness; is the capacity to mobilise community assets as they are needed in the event of a disaster. Assets may include agents, physical, financial, geographic, or social assets; and

- (iii) Cyclical learning; taking the outcomes of past events and identifying weaknesses so that they can be avoided in future. This will innovate improved performance and promote agents to learn new skills as necessary.

Agents are capable of using their experience and expertise to anticipate external stresses. Their ability to act will be mandated by their authority within their organisation and the finance and other resources available to them. These capacities may be developed over time and prior experience of disasters will greatly benefit them from cyclical learning strengthening their resilience capabilities. Governance and the decision-making processes that build resilience should be participatory and inclusive for the entire community allowing the most vulnerable groups to play an active role in avoiding impacts (Lebel et al., 2006). Resilience requires that local government and service providers be held accountable to the communities that they serve and become proactive in building coordinated resilience across communities at all levels (Moser and Satterthwaite, 2010).

In addition to interactive governance, local government and service providers should foster learning and change to build their agent capacity. Effective innovation requires the publication of knowledge and management methods so that they can be criticised by stakeholders across industry disciplines and society (Berkes, 2007). In their assessment of the key aspects linking agents and systems, which should be considered as to the enhancement of resilience, Huntjens et al. (2012) put forward the following list:

- (i) Rights and entitlements – ability of the agent to access resources and deploy them during a disaster event;
- (ii) Decision making processes – decision-making which affects the wider community should follow good governance principles of transparency, accountability and responsiveness;
- (iii) Information flows – decision making agents should have access to data as quickly as it becomes available to enhance their decision-making capability about risk and vulnerability; and
- (iv) Application of new knowledge – agents and governing bodies that facilitate the exchange of information between other bodies and communities enhance their resilience.

Once information flows and awareness of the key issues has been established agents must also be given the necessary resources so that they can act. The issue of adequate funding for disaster has been demonstrated as a primary issue for achieving resilience during post disaster reconstruction (Resosudarmo, 2017). During pre-disaster mitigation or basic construction processes, decision-makers have time to review supply chain and resourcing issues and often have a choice between a range of suppliers. In contrast post-disaster projects necessitate that decision makers abide by the local reality of often highly limited resources and constraints, of lack of access to resources, and of the chaos originated by the disastrous event (Chang et al., 2011). A shortage or unavailability of funds for building resources self-evidently hampers the reconstruction of any project. Da Silva (2010) recognized the need for funding to be made available for long term reconstruction through systematic planning ensuring the availability of, or capacity to purchase, building resources. Pre-disaster preparedness necessitates that resilience disaster funding is secured to ensure the effectiveness of post-disaster recovery efforts. Cooperation and partnerships across institutions within the STS at the local level and between governments at the national level, and any other relevant stakeholders should be developed to ensure resources and key personnel can be mobilised.

The successful implementation of coordinated reconstruction work requires policies and legislation to ensure the delivery of functional capacity beyond pre disaster levels (Deen, 2015; Segal et al., 2017). Current policies and legislation across the areas of planning, CI standards, environmental impact, public health, and energy efficiency should be reviewed to develop a specific legislative portfolio compatible with post disaster reconstruction needs. Current legislation should be updated to reflect the increased impact of climate change and the associated heightened risk, particularly in urban areas. By way of example a combination of legislation mandating the retrofit of outdated building materials and the use of new technology in coordination with flexible policy to provide decision makers with guidelines for various disaster types should be issues. In the event of a disaster it is necessary to provide guidelines on resourcing issues including price controls, governmental subsidies in the affected area, quality supervision, and strict building standards (Platt, 2017; Bilau et al 2017). This literature influenced the design of Stage 6 of the RMF 'Recovery and reconstruction', for further details see Section 4.8.

2.6 Resilience Analysis

This Section addresses RQ1 '*How are resilience analysis strategies currently being employed in conjunction with STS?*' and suggests how resilience analysis may overcome the shortcomings of traditional risk analysis. The goal of resilience management is to ensure the focal system either adapts to remain within a socially and technically desirable equilibrium or transforms into one (Folke et al., 2010). In order for an equilibrium to be maintained, key agents must have sufficient adaptability across the STS levels. They must also be capable of transforming the system from a less desirable to a more desirable regime; this will require multiple agents working together.

Management actions seek to preserve the systems functionality and control key STS properties which will enable the system to adapt and reorganize in the event of a disaster (Baxter and Sommerville, 2011). The primary focus of resilience management is on deliberately maintaining and enhancing system resilience over the long term. Agents must therefore be aware of how different aspects of the STS interrelate, what characteristics enable resilience and how to improve resilience prior to, during, and in the aftermath of, a disaster event. Resilience management involves implementing strategies for fostering and manipulating the system to minimise areas of weakness and maximising those system assets which improve resilience (Longstaff et al., 2010).

Research carried out by Linkov et al. (2015) has shown that resilience concepts applied to CI have developed around the overlapping nature of systems. It has further been suggested that whilst risk can be considered a component of resilience, resilience itself includes a time application that risk does not (Linkov et al., 2015): "*...Risk management helps the system prepare and plan for adverse events, whereas resilience management goes further by integrating the temporal capacity of a system to absorb and recover from adverse events, and then adapt.*"

CI resilience has been defined as the '*capacity to adapt to complex and risky environments*' (Bergstrom, Van Vinsen and Henriqson, 2015). Resilience engineering adopts a systemic view of the system's ability to '*respond, monitor, anticipate and learn*' (Hollnagel et al., 2009). In an attempt to address the complexity of STS, modern resilience assessments need to develop combined quantitative and qualitative factors (Vugrin et al., 2010). Coaffee et al (2008) give an example of integration of

environmental efficiency and measures for enhancing resilience to man-made terrorist threats for cities, two strategies that are treated as separate in literature. In terms of analysing the resilience of STS it is necessary to combine engineering resilience with community resilience (De Florio et al., 2014).

The overlapping nature of modern systems has quickly out grown traditional risk assessment methodologies (Sikula et al., 2015). STS are complex systems however the analysis of these systems is often carried out in a linear fashion and siloed fashion which fails to account for the surrounding community or other dependent CI. Current risk based assessment models often assume that supporting systems will continue operating regardless of any disaster event (Cutter et al., 2008). This assumption effectively decouples the supported infrastructure from its supporting infrastructures and focuses on the dependencies rather than on the interdependencies of the infrastructures in question. A clear understanding of the STS context is needed to avoid disastrous results and is thus vital in analysis of the interdependency between infrastructures (Boaru & Badita, 2008).

This expansion of complexity has out stripped single-industry safety systems, and thus this research will reflect a change in emphasis from one of CI protection to the much wider approach of STS resilience. This research characterises urban resilience in context and articulates what is required to design and implement resilience measures, to raise awareness with system decision makers and stakeholders, and to introduce resilience management tools as a means to address disaster events. Existing risk management standards contribute to these aims at a base level, and typical risk assessment matrices used by CI operators and city management are based on the International Organisation for Standardization (ISO) risk management standards. It is important to understand and develop resilience from a starting point of current risk practices to facilitate a transition to an urban resilience-based analysis of STS. Therefore ISO 31000 is particularly informative for the development of this methodology.

In addition to international and European strategies and projects on resilience and STS, this research was informed by the relevant international standards on risk management and resilience, such as the following:

- ISO 31000: 2009, *Risk management – Principles and guidelines* (ISO, 2009);

- ISO/IEC 31010: 2009, *Risk management – Risk assessment technique* (ISO, 2009);
- ISO Guide 73: 2009, *Risk management – Vocabulary* (ISO, 2009);
- BS31100 Risk Management Code of Practice (British Standard, 2008); and
- UNISDR Sendai Framework (UNISDR, 2015).

Metrics are needed in order to provide a sound basis for the development of effective decision-making tools for multi-hazard environments. The UNISDR has reported data summarising the extent of exposure to various hazards at a global level, the hazard most often listed is flooding. Resilient systems should be developed to meet sustainability requirements defined by the three pillars of sustainability by reconciling environmental, social equity, and economic demands (Ayyub, 2014).

In order to prepare to address these issues it is necessary to put an approach in place that enhances the system's resilience. There are several catastrophe models for measuring economic losses however, these have been designed for community or regional after effects of disasters and none of these focus on CI (Martinelli et al., 2014). The assessment of STS disaster resilience is also required in order to pursue the goal of measuring system progress for resilience enhancement over time (Gracceva, and Zeniewski, 2014). The aim is to compare quantifiable levels of resilience from system to system in order to help identify and develop interventions and evaluate their effectiveness.

After several decades of research into the field the resilience concept has failed to be transferred into an operational tool for CI management which incorporates community needs (Klein et al., 2003; Clarke et al., 2016). Quantitative models aim to assess resilience by measuring performance of the system, regardless of the structure of the system. These measures are comparable across different system contexts with similar underlying logic. Current practice in resilience assessment and promotion for CI is too often limited to specific, internal technical factors. Systems resilience is most often ranked on the time taken for the system to return to a pre-disaster level of functionality. This metric is problematic as it fails to acknowledge the system's ability to reorganise

and become more productive than the pre-disaster equilibrium i.e. for the system to improve as it is repaired.

Through the literature there are five key classification types in the quantitative modelling and planning of resilience (Hosseini et al., 2016). The following models and approaches to systems resilience analysis show a clear transition from narrow, technical risk assessments to a wider socially and organisationally informed extension of risk assessments as CI resilience.

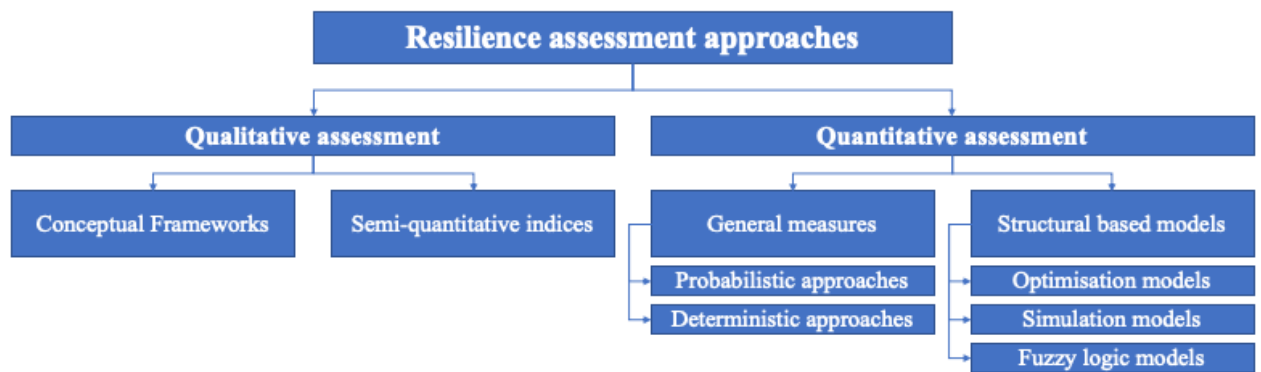


Figure 2.5 Classification scheme of resilience assessment methodologies (Hosseini et al., 2016).

Deterministic models are the most widely used as they are straight forward to adapt and they do not incorporate uncertainty. These models emphasise the importance of a systems robustness, resourcefulness and redundancy. Deterministic models analyse the quality of effected systems to their original planned output.

Probabilistic models monitor the loss of performance and the length of time taken for system recovery to full functionality. In addition, a third metric of system component reliability may be added here however this is dependent on expert knowledge which may prove in the first instance of a particular disaster event.

Optimisation models show the importance of a speedy return to functionality. These models may also take the minimum level of functionality required for the necessary output to be achieved.

Simulation modelling focuses on the pre-disaster stage of resilience and preparedness for unforeseen events. Simulation models further emphasise the importance of flexibility and redundancy as elements of resilience.

Fuzzy Cognitive mapping models have been used to show the redundancy and adaptability as the primary components of infrastructure resilience.

Input-Output Models: Earlier input-output models classically identify interdependencies among different social sectors and analyse breakdowns within the CI system and to a set of sectors and the resulting domino effect between systems (Rose and Liao, 2005). The issue remains that these models reflect only “business-as-usual” conditions, when they are based on historical data. These models are linear in their approach, which has been less effective when analysing complex social systems.

Hazus Model: This model software developed by FEMA to estimate different types of losses generated by a natural hazard. The software primarily operates at a high level and so the application for CI systems is limited. Martinelli (et al., 2014) used this to build a framework which divides losses on a direct and indirect basis. The basic HAZUS inspired models assume that relocation occurs if the damage state of the building (or system) is greater or equal to moderate. The goal of this model is to model the losses of a specific region. This model does not take into account the possibility that industries may be forced to relocate post crisis.

CGE Model: Computable General Equilibrium (CGE) analysis is the state of the art in regional economic modelling. CGE modelling acts as a useful framework for the analysis of individual businesses in markets, in particular for impact and policy analysis. The CGE model captures both price and quantity interaction through the explicit inclusion of market forces (Rose and Liao, 2005). CGE models may be recalibrated to include CI disruptions.

DROP Model: The Disaster Resilience of Place model designed by Cutter et al. (2008) is specifically designed to improve comparative assessments of disaster resilience at the community level. It highlights “leadership” on the planning and implementation of Disaster Risk Reduction strategies. Under this model key resources of place should be identified and protected because they are crucial for the post-disaster resilience of the local communities.

The ISO standards and other risk literature outlined here inform this research and many of the resilience assessment methodologies outlined here are risk based or contain risk-based elements. However, a full critique of risk management is beyond the scope of this thesis.

Mitigation and adaptation have proven to be useful strategies to prepare communities for disaster events and to reduce vulnerability (McDaniels et al., 2008). A community's vulnerabilities are often only made fully clear after the disaster event has taken place. In order to reduce vulnerability, mitigation strategies can be put in place for certain disaster scenarios however true community resilience is needed to achieve an adequate post-disaster response. The critical characteristics of resilience are:

1. Robustness; avoidance of direct and indirect economic losses
2. Redundancy; untapped or excess economic capacity
3. Resourcefulness; stabilising measures (e.g., capacity enhancement and demand modification, external assistance, optimising recovery strategies), and
4. Rapidity; optimising time to return to pre-event societal function levels

Carpenter et al. (2001) explain that the multifaceted nature of resilience creates challenges for the development of accurate measurements. The conversion of initial conceptual frameworks to working assessment methods is complicated by the need to include baseline conditions as well as the impacts of the disaster event itself (Pelling, 2010). These factors vary across the functionality of CI, institutional, economic, societal elements. The focus of resilience must be narrowed in terms of what elements need to be more resilient and what it needs to be resilient to. Natural disasters create many different event characteristics which are amplified or reduced based on the antecedent conditions. The effects of flooding on communities will vary depending on the location, the frequency, the duration, and the rate of onset and (presumably) the antecedent conditions.

Resilience analysis and assessment has been carried out across a wide range of subject areas and quantitative indicators are used in the majority of cases as external references are required to underpin the assessment (Schneiderbauer and Ehrlich, 2006). This allows indicators to be used to analyse changes in resilience over time of a particular location/community, as well as providing a comparison of the resilience of two or more communities to one another. In order for the continuous tracking and comparison of resilience levels, indicators must be robust, reproducible, simplistic, data must be accessible and they must be relevant to the area being studied and the hazard affecting it (Gall, 2007; Birkmann, 2006; de León and Carlos, 2006).

In 2003, Freudenberg outlined a number of specific steps for the process of indicator development which are followed through the development of the Disaster Resilience Indicators (DRI) indices. The first of these is to form the rationale for indicator variable selection and weighting through the development of a theoretical framework. This is followed by testing and verifying the indicator data.

Not only is it vital to evaluate and benchmark the baseline conditions that lead to resilience, but it is equally important to measure the factors contributing to adverse impacts and the diminished capacity of a community to respond to and rebound from an event (Cutter et al. 2008). Just as companies have identified areas of opportunity and benchmarked their performance against industry standards, governments are finding it useful to evaluate the performance of communities in terms of their comparative resilience. While the latter is partially to attract public interest in disaster loss reduction, it also provides metrics to set priorities, measure progress, and aid in decision-making processes. Composite indicators (often referred to as indices) are useful tools to accomplish this task. We use the term “composite indicator” to designate a manipulation of individual variables to produce an aggregate measure of disaster resilience. An indicator is a quantitative or qualitative measure derived from observed facts that simplify and communicate the reality of a complex situation (Freudenberg 2003). Indicators reveal the relative position of the phenomena being measured and when evaluated over time, can illustrate the magnitude of change (a little or a lot) as well as direction of change (up or down; increasing or decreasing).

A composite indicator is the mathematical combination of individual variables or thematic sets of variables that represent different dimensions of a concept that cannot be fully captured by any individual indicator alone (Nardo et al., 2008). Composite indicators are increasingly recognized as useful tools for policy making and public communication because they convey information that may be utilized as performance measures (Saisana and Cartwright, 2007). Numerous approaches for measuring composite indicators at both global and local scales have emerged. Many of these are central to the environmental hazards and natural disasters community as they were developed to capture a society’s vulnerability to social and/or environmental change. Among these are metrics created to assess the susceptibility of small states to

fluctuations within international economies (Briguglio 1995; Easter, 1999) and indicators designed to measure national wellbeing (Neumayer, 2001; Prescott Allen, 2001). Also significant are composite indicators of social vulnerability. This literature influenced the design of Stage 3 of the RMF ‘Disaster Resilience Indicator assessment’, for further details see Section 4.5.

2.7 Identified Literature Gaps

The literature review highlighted that practical resilience concepts which offer all-encompassing integrated approaches to planning for, responding to, and recovering from disasters are required to ensure that the basic functions and structures of the STS remain intact. This is especially important due to the increasing system complexity and interdependency associated with current STS, where the cascading effects of a system breakdown on other interconnected systems could negatively affect the overall well-being of the affected urban society (Mitchell and Harris, 2012). In addressing this core concept a number of literature gaps became apparent which are described in this section.

Planning for Resilience: Current assessment tools point to where weak points in a system and enable to allocation of resources. However, there is a lack of supporting literature explaining and understanding the trade-offs among resources available and the resilience achieved through investment in vulnerability reduction (Sharkey et al., 2015).

Community Resilience: Resilience assessment models have primarily focused on the economic cost of disruption and repair. These assessment models fail to encompass the disruption of CI systems and their influence on the communities that rely on them (Pant et al., 2014).

Resilience Indicators: indicators are a useful tool for benchmarking the baseline conditions that lead to resilience. The National Institute of Standards & Technology (U.S.) have acknowledged the lack of resilience indicators for the identification of critical components in STS. Once identified these indicators must then be capable of resilience measurement (Larkin et al., 2015).

STS resilience: analysis cannot be achieved without an operational model of urban resilience measurement and management. Such identification schemes as well as models are however currently lacking in the literature.

Interdependent Processes and Systems: Highly coupled relationships between CIs are seldom addressed in the literature. The proposed methods of interdependent assessment models exist they focus on identified risks. Although interdependency-based strategies are shown to produce the largest total protection for a particular risk this has not been developed for unknown risks and resilience assessment (Ouyang et al., 2015).

The identification of a set of system components, along with the development of a resilient model that would help to assess the vulnerabilities of the system to an unforeseen disaster event, will contribute towards the development of a systems based economic and social resilience analysis model (McLellan, B. et al., 2012). This research seeks to advance this by developing a holistic approach to STS resilience which also considers exogenous, social and organisational factors, as well as the issues of interdependency and cascade failure (Larkin et al., 2015). This literature influenced the design of Stages 4 and 5 of the RMF ‘Prioritisation of vulnerabilities’ and , ‘Increasing the adaptive capacity’ for further details see Section 4.6 and Section 4.7.

2.8 Summary

This chapter reviewed the development of resilience theory from its introduction in ecology, followed by its application in engineering and community resilience. The review continued with analysis of STS development and applying the concept of resilience to STS. Section 2.6, highlights the ongoing transition from a more limited CI protection which is siloed in nature to the more holistic approach of STS resilience. Further advancements were proposed to incorporate community resilience and CI resilience in a single resilience framework by viewing the urban environment as a series of interrelated STS. A number of approaches to resilience measurement were reviewed with the description of several resilience models were highlighted. The alignment with community and the potential to incorporate CI resilience demonstrated in the DROP model suggests that it would be a strong conceptual basis for indicator selection.

Following the literature review and the work on the RESILENS project the six high level stages of the proposed RMF were selected. Standardised terminology and integration of resilience approaches were derived and adapted from ecological, community, and engineering resilience approaches with a view to the development of a holistic resilience approach, which would be applicable to STS. The development of each of these stages, the associated tools and their testing is further detailed in Chapters 4 and 5. Input was also taken from the finding of the interview process and the case study findings of the evaluation and validation undertaken as part of this research. The RMF components are outlined here:

- (i) **Building resilience awareness** – based on the need for clear understanding and communication between agents and stakeholders, the rationale for this is outlined in Section 2.4.
- (ii) **Selection of essential organisational components** – based on the need to identify the core assets within the STS, the rationale for this is outlined in Section 2.3.
- (iii) **Disaster Resilience Indicator (DRI) assessment** – designed to give a baseline resilience benchmark which can be monitored as improvement measures are taken. The rationale for this is outlined in Section 2.6.
- (iv) **Prioritisation of vulnerabilities** – designed to plot and visualise agent interactions with other systems and stakeholders. The rationale for this is outlined in Sections 2.3, 2.4. and 2.6.
- (v) **Increasing the adaptive capacity** – selected in order to adopt measures including new technologies to improve the resilience of the system based on the weaknesses identified by the DRI. The rationale for this is outlined in Sections 2.2, 2.4 and 2.5.
- (vi) **Recovery and reconstruction** – implement adaptation strategies and retrofit the STS with resilient materials. The rationale for this is outlined in Section 2.5.

CHAPTER 3 METHODOLOGY

This chapter describes the methodological design of the research addressing the questions identified in Chapter 2. The research goal is to establish a standard and practical measure for resilience in relation to urban contexts.

3.1 Introduction

The concept of resilience continues to grow in popularity and application across numerous disciplines, with many indices and frameworks developed seeking to standardise methods of assessing the properties of resilience (Tyler and Moench 2012; Ouyang et al., 2012). There is consensus that resilience needs to be measured and managed, but these frameworks are generally scenario-specific employing varying definitions of resilience, constructed using indicators and metrics unique to their setting. They are utilised for different purposes and as a result they are rendered unusable in any other context than the one that they were specifically designed for. Through the literature review in Chapter 2, it became clear that there is a difficulty in establishing a measure that is accurate, generally applicable and fit for purpose (Bruneau et al., 2003; O'Rourke, 2007; Fisher and Norman, 2010; Bakkensen et al., 2016). Further, there is no international standardised measurement approach for urban resilience.

The research is a process-oriented approach to resilience assessment. This approach develops from a foundation of risk management, which is enhanced through the consideration of resilience for use in the complex systems of the urban environment, namely critical infrastructure (CI) and the societies they support. By building on the foundation of traditional risk management, resilience management reflects wider system properties rather than specific risk scenarios. Resilience management is also more flexible than traditional risk management, allowing for straightforward application depending on the context using qualitative feedback from qualified experts in addition to standard quantitative measures. This flexible nesting of qualitative and quantitative approaches allows for the consideration of a range of resilience properties across a range of disaster types.

This research characterises urban resilience in context and articulates what is required to design and implement resilience measures, to raise awareness with system decision makers and stakeholders, and to introduce resilience management tools as a means to address disaster events. The process of developing standardised practical resilience tools begins by reflecting on the methodological framework and the methodological considerations as illuminated in the state of the art and gap analysis as outlined in Chapter 2. Fundamental to this work is reflection on the respective epistemological underpinnings and to examine the rationale of the proposed approach including its appropriateness in comparison to other methodologies put forward in the body of urban resilience research.

This methodology is the conceptual pathway for the development and feasibility testing of the Resilience Management Framework (RMF). In this chapter a methodological framework for developing the RMF is advanced, an understanding of the methodological underpinnings and sequencing of the developed tools is also outlined. In doing so, I draw upon the literature review carried out in Chapter 2, and reflect on the methodological approaches described there to enhance resilience for urban networks. In this methodology I propose a further advancement to incorporate community resilience and CI resilience in a single resilience framework by viewing the urban environment as a series of interrelated STS. The advances in STS resilience, as outlined in the literature review Section 2.5, highlights the on-going transition from a more limited CI protection to the more holistic approach of STS resilience.

The stages of research development for the RMF are outlined in Figure 3.1 below.

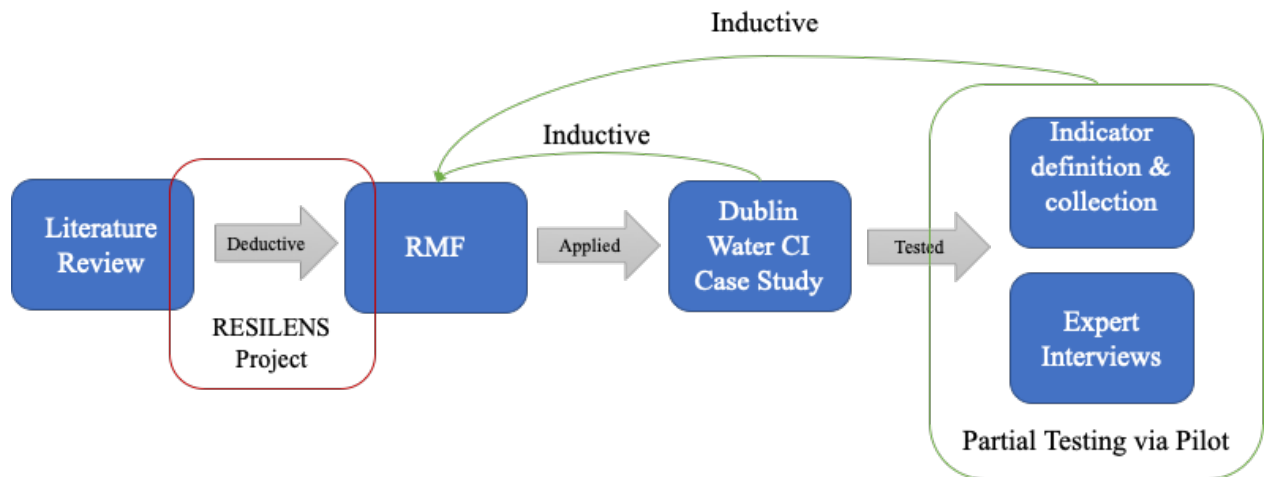


Figure 3.1 Methodology Diagram

3.2 Research approach

As it is used throughout this thesis, the term ‘research’ refers to the critical enquiries and systematic study of urban resilience (Cooper et al., 2006). Further, the term ‘research approach’ refers to the theoretically informed way of undertaking the research. This section explains the philosophical stance adopted and locates the research approach in the broader academic landscape. A hybrid frame of reference composed of risk management, resilience thinking and STS informs the proposed approach. Together, these guide the approach and overall framework that are used to address the research questions posed in Chapter 1. This chapter is initially concerned with analysing the findings from the literature review in Chapter 2 and considers the approaches to define and achieve urban resilience as the basis for providing a methodological approach for developing the initial draft RMF. The first version of the RMF incorporated the scientific literature in relation to STS, resilience management and risk assessment put forward in Chapter 2, before being further informed by the interviews and refined to deliver the final iteration of the RMF. This framework is then applied to the case study for analysis.

Key to the design of this research has been the conceptualisation of cities as a system of systems, operating in a complex and uncertain context, which necessitates transformational approaches and tools that promote resilience enhancement, based upon social and organisational factors, adaptability and on-going learning. In simple terms, the methodological framework seeks firstly to specify the target objectives, the ‘what’,

being aimed for in enhancing the resilience of urban networks advancing through the advancement of the RMF. The methodology then sets out the ‘how’ this will be achieved and the range of tools that will be designed and deployed.

The overall methodological approach put forward was constructed following a nonlinear sequence. The empirical investigation is grounded in the review of the urban resilience literature, which was reviewed on a continuous basis as research tasks were completed, before being validated through the analysis of the findings from the case study and through the expert panel interviews. These two phases overlap as various tasks were completed. This initial literature review was developed during the initial research phase and coincided with similar research activities on the Realising European Resilience for Critical Infrastructure (RESILENS) projects. The research was also influenced by ongoing work with TCD Connect, Dublin City Council (DCC) and Smart Dublin staff. The interviews were conducted during the finalisation of the case study; thus they help to inform and shape the stages of the RMF. The purpose of this is to assess the effectiveness of the methodology underpinning the RMF and its application to the case studies.

This research is interdisciplinary and draws from a diverse range of disciplines including risk management, engineering, urban planning, computer science and social science. In particular it utilises literature from engineering, risk management, and the social sciences. The breadth of the subject matter creates difficulties in carrying out research in a cohesive and coherent fashion. It involves interpreting and understanding knowledge from sources across a range of subject areas, which may not have been specifically designed for urban resilience enhancement. It is therefore necessary that, to an extent, this methodology is experimental in nature and indeed in some areas, involves the hybridisation of methodologies across different research fields. The conclusions drawn from the expert interviews and the lived experience of the researcher are internally consistent and are supported by evidence and validated through the case testing of the RMF in Chapter 5. This became all the more clear through the interview process with the key flood protection experts. What follows is an account of the entire research process.

3.2.1 Resilience Research

The overlapping nature of modern systems has quickly outgrown traditional risk assessment methodologies. Increasing complexity of interrelated systems has outstripped single-industry safety systems, and thus this research will reflect a change in emphasis from one of CI protection to the much wider approach of STS resilience. Resilience provides a transdisciplinary theoretical framework and analytical lens for examining the complex relationships and dynamic interactions between people, the systems they develop and wider society. A ‘resilience perspective’ (Folke 2006) or ‘resilience thinking’ (Walker et al., 2004) embodies an integrative ‘actors-in-systems’ worldview (Friedberg and Crozier 1980).

After several decades of research into the field, the resilience concept has failed to be transferred into an operational tool for STS management needs (Klein et al., 2003). Linkov et al. (2014) have outlined that there is a need for resilience based approaches to be adapted for technical approaches in infrastructure systems. Further, Baum (2015) supports this by outlining the benefit of using resilience as a framework for unknown and unforeseeable events.

Quantitative models aim to assess resilience by measuring performance of the system. The objective is to create measures that are comparable across different system contexts with similar underlying logic. Current practice in resilience assessment and promotion for CI is too often limited to specific, internal technical factors and fails to take into account the human factors that influence resilience and organisational management.

As a mixed methods approach to STS research, resilience and its related concepts provide an organising framework for understanding the complex adaptive dynamics of STS. Resilience thinking addresses the often contradictory, but nevertheless vital, interplays between persistence and change, and disturbance and reorganisation. Such nonlinear dynamics are essential for maintaining the key functions, structures, feedbacks and therefore identity of whole STS (Manz and Stewart 1997). Resilience thinking deals with complex adaptive systems properties, which are described in Chapter 2. It takes into account the complex interactions, interdependencies and feedbacks between technical systems development and social dynamics (Geels, 2004). Resilience thinking seeks to understand the qualities of STS that must be managed

(deliberately maintained and enhanced, or diminished and lost) to enhance the system in the face of a disaster event.

3.2.2 Methodological perspective

This section outlines the research approach and the researcher's worldview as a critical realist. This research takes a "pragmatic" approach, which considers a realist, ontological and post-positivist epistemological positions (Denzin and Lincoln, 2010). The research adopts a case study approach, which is discussed in Section 3.3.4 (Van Teijlingen and Hundley, 2001). A mixed methods approach is used, employing quantitative and qualitative elements. The researcher's position in terms of ontology, epistemology, human nature and methodology are also explored further here.

A Post-Positivist epistemology

Insights about the limitations of positivism and modernity imply that you have to understand your own place in the world and what you are bringing to the research by way of assumptions about knowledge. Investigating your own epistemologies and understanding how they affect you as a researcher is an essential part of the post-positivist approach. As part of this investigation, you come to some understanding of how you and others construct and maintain perceptions of the world. Examining your epistemology involves looking at the underlying assumptions you use to make sense of your "day-to-day" life. 'You cannot claim to have no epistemology. Those who so claim have nothing but a bad epistemology' (Burrell and Morgan, 1979).

It is assumed that data, information, interpretations and outcomes exist in context and these can be tracked to their sources. The logic used to interpret the data and derive conclusions is made explicit in the narrative (Mertens, 2010). This research is embedded in a normative context that has interacting social and technical dimensions, and therefore a mixed methods research strategy is best suited to studying complex issues involving these interactions. Emphasis is placed on credibility, transferability, practicality, and confirmability, rather than objectivity at each stage of the RMF development (Denzin and Lincoln, 2005b).

On being a "Critical realist"

A realist ontology postulates that the social world external to individual cognition is a real world, comprised of hard, tangible and relatively immutable structures. Whether or not we label and perceive these structures, the realists maintain, they still exist as empirical entities. For the realist, the social world has an existence that is as hard and concrete as the natural world (Burrell & Morgan, 1979).

Post-positivism is a rejection of the central tenets of positivism with the view that the scientific approach is not distinct from how we think in our everyday lives (Willis, 2007). Scientific reasoning may be viewed as an extension of a common-sense reasoning process. Although the processes may be viewed as fundamentally similar, the degree to which scientific procedures is applied will be necessarily more rigorous. By way of example, scientific procedures are more rigorous and aim to ensure that observations are verifiable, accurate and consistent. This is not normally the case with day-to-day proceedings. A form of post-positivism is the philosophy of critical realism, which believes that there is a reality independent of our thinking that science can study (Fox, 2008).

For ‘critical realists’ agency and structure is central to their ontology. This ontology differentiates between modes of reality so they are not forced into a dualistic situation whereby, if structures are not materially real, then they must be ideally real. Critical realists are not forced to choose between, or to privilege, either of the polarities. Neither do they pursue a subject-orientated research agenda, nor do they focus solely on the object (Mingers et al., 2013). A critical realist leaves room for both/and subjective and objective truth but requires that whatever truth claims are made must be subject to and stand up to critical analysis (Sayer, 2012).

Critical realists refer to entities as concept mediated, they go beyond the positivist position of treating representations as unproblematic representations of an object. Critical realists are not prohibited from reflecting deeply on the nature of the subject. They share the view that human beings have a ‘timeless’ capacity to think and act creatively, and to exercise their free will (Fleetwood, 2005).

This perspective informs the RMF design process to improve urban resilience management approaches for city administrators, and infrastructure service providers,

and the trialling of the output tools has generated new knowledge on this topic. This is reflected in the initial research question which was formulated as RQ3 *'How can STS be managed to reduce vulnerability to multiple hazards, increase capacity to tolerate and deal with change, and so achieve regional urban resilience?'*. From this question stemmed the aim and objectives stated in Chapter 1 to design the RMF for STS.

3.3 Research design and strategy

This research is embedded in a socio-technical environment and this had led to the adoption of a mixed methods research strategy. A mixed methods approach is more suited to the study of complex systems, issues and problems that involve human decision makers interacting with infrastructure systems and wider society. A single case study of Dublin, Ireland was selected in order to apply and test the outputs of this research. The Dublin case study is conceptualized to take into account the systems supporting the greater Dublin area serving as a macro region STS. The research design focuses on a methodology to develop resilience indicators using Geographic Information System (GIS), to develop practical management tools and to elicit expert opinion regarding the tools developed and their application for flood protection in Dublin. Interview questions were designed to gather information and validate the practicality of the proposed RMF from a panel of experts with knowledge and responsibility for flood management in the city.

This research involves the design, construction and practical testing of the RMF. The RMF involves complex patterns that cannot be studied from the perspective of any one discipline and to the methodology integrates elements from risk management, engineering, computer science and the social sciences as well as urban resilience theory. Therefore, this research considers the Dublin case study from multiple perspectives and as a preliminary test of the proposed RMF, elicits the expert opinion from across a range of disciplines. This interdisciplinary approach provides a more holistic understanding that better reflects the complexity of the RMF process in Dublin and one hopes other cities with similar characteristics.

A critical realist approach to case research involves developing a research question (Section 1.3.2) that identifies a research phenomenon of interest, in this case urban resilience of STS. This phenomenon is then analysed in terms of the key agents and bodies involved, discernible events, the relationships between these and how they interact can be identified. The case can then progress by gathering data on ongoing or past events, but importantly the data must be interpreted in the context of the challenges faced by the agents in the real world case. This is a cyclical process of research gathering data, contextualising it and reflecting on the implications. The final stage of the case is to analyse the underlying mechanisms of the case, (Easton et al., 2010).

3.3.1 Mixed methods research strategy

The research strategy is the overall plan of action the researcher uses for conducting a research project and achieving its aims (Denscombe, 2010). The research strategy consists of the rules directing the research and guides the researcher in making methodological choices. In effect, a research strategy is the set of methods selected and used according the rules and functions at different stages of the research process (Berg, 2001).

Commonly, a distinction is made between quantitative and qualitative strategies in terms of contrasting characteristics. The key difference between a qualitative and a quantitative approach relates to the means of data collection and analysis. The quantitative paradigm is often based on positivism; measurement is the main approach to collecting and analysing data with a deductive testing approach. Science is characterised by empirical research; all phenomena can be reduced to empirical indicators which represent the truth (Sale et al., 2002). Quantitative strategies are ontologically objectivist in that social reality is regarded as objective fact.

Contrastingly, the emphasis of qualitative research is on process and meanings. Techniques used in qualitative studies use an inductive approach to generate theories and include in-depth and focus group interviews and participant observation. These techniques rely on the researcher's interpretation of the data and are constructionist in that results are a product of perception (Walliman, 2017). Samples are not meant to represent large populations. Rather, small, purposeful samples of articulate respondents

are used because they can provide important information, not because they are representative of a larger group (Reid, 1996).

Onwuegbuzie and Leech (2005) view this distinction as too rigid and consider that using only one of either qualitative or quantitative research to be limiting, stating that the '*mono-method research is the biggest threat to the advancement of the social sciences*' (p.384). A more practical research approach involves a choice a different techniques to address particular questions through the research project as necessary (Bryman, 2013, 2016; Creswell, 2009; Mertens, 2010). This mixed methods approach is becoming more popular as a combined quantitative and qualitative approach for collecting and analysing data (Hesse-Biber, 2010; Bryman, 2016).

Mixed methods refers to a research strategy that combines the conventional research paradigms of quantitative or qualitative research and combines methods with different underlying assumptions (Denscombe, 2010). Creswell (2012) explains that this combination of the two paradigms provides the researcher with more tools than using either in isolation would.

Utilising a mixed methods approach minimises the weaknesses of each method and can improve the validity of the research (Melkert and Vos, 2010). Mixed methods research is particularly applicable in the testing the theories, or in this case the framework, which is constructed before the data is collected. The researcher may construct a situation that eliminates the confounding influence of many variables, allowing one to more credibly assess cause-and-effect relationships. Data collection using some quantitative methods can be relatively quick (e.g., phone interviews). However, the researcher must be careful not to miss out on phenomena occurring because of the focus on theory or hypothesis testing, rather than on theory or hypothesis generation (called the confirmation bias). Furthermore, Small (2011) critiqued the problem of commensurability and the problem of continuing specialisation, including methodological specialisation.

For this research I adopted a mixed methods research strategy to deal with the complexities of the RMF itself and the target Dublin water management system case.

Onwuegbuzie and Leech (2005) define mixed methods research as “*the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study*”. From a philosophical perspective, it is considered a logical and practical alternative to the common qualitative and quantitative paradigms and is viewed as the third research movement. Through this research aspects of both standard paradigms are utilised as necessary, the design of the RMF and the indicators in particular are quantitative and this research output is verified by expert opinion through a qualitative interview process. The case testing of the RMF is designed to prioritise the resolution of organisational issues and the impacts for the agents who experience them (Coghlan and Brannick, 2005). This is explored further in Section 3.3.4. From a positivist, determinist perspective, a mixed methods research strategy is generally suited to studies that seek to understand and interpret case studies where new frameworks are being theorised and tested. Various methods can potentially be used in mixed methods research; the methods used in this research project are described in further detail in Section 3.4.

3.3.2 Design Methodology

The design of the RMF and the tools it comprises of are built on a foundation of the literature review and informed by the researchers work on the RESILENS project. The founding principles of these tools are outlined in this section. The basis of the individual tools themselves are described in detail in Chapter 4, 5 and 6.

Urban resilience as a strategic approach is particularly fitting for complex STS that are dynamic and face a high degree of uncertainty (Walker et al., 2002). Resilient systems ensure that functionality is retained or operable immediately after a disaster impact, despite operational disruptions (Bruneau et al., 2003). In order for city managers, town planners and infrastructure operators to increase urban resilience, a framework is needed to provide guidance for how urban resilience means can be measured and improved in relation to STS.

In addition to the system itself, the framework design incorporates the actors or agents within the STS. These include decision makers in public and private sector

organisations who have an interest in, or are responsible for, maintaining service during a disaster. An agent's interests may change based on the strategy applied, their experience, and will differ between agents. It is important to recognise these interests and to incentivise the agent's interaction with the research by emphasising the motivations they have. As detailed in the case study, maintaining employment levels for the team made the agents sceptical of any new technology, which could lead to staff redundancies. Through interactions, interviews and by making information available to them, the agents' behaviour may change over time but the results may manifest themselves in unexpected ways (Bruneau et al., 2003).

These agents, some of whom take part in the expert panel described in Section 3.4.3 below, were involved in a collaborative partnership with the researcher. Eden and Huxham (1996) outline that the involvement of agents in an issue of concern for them will ensure their continued enthusiastic involvement in the tool development. In order for this framework to be applicable across contexts, it should remain uncomplicated and be comprehensible to lay readers.

3.3.3 Case study approach

A brief review of the literature regarding participatory research methods and techniques used in the risk management and social sciences was undertaken to determine suitable candidate methods and techniques for eliciting and reporting (aggregated or individual) expert opinions. In order to fully test the RMF and to understand the complexity of STS, it was apparent that an in-depth single case study was appropriate and therefore it was selected (Yin, 2003). This also follows the research process from researcher's work on the RESILENS project, where a case study method was identified as the primary research method. A single case study, of CI in Dublin viewed as STS, was selected as the research approach.

The case study approach enables the researcher to explore and develop detailed knowledge based on extensive data collection in a particular setting or case (Creswell, 2009). The aim of the case study is to provide an in-depth account of the feasibility of the RMF and its application to the water management system in Dublin (Denscombe 2010). In order for the research to produce verifiable, replicable and practical outputs, the case study involves clearly defined system boundaries, detailed definitions of key

aspects and descriptions of the Dublin STS. Following this, analysis is carried out the information collected from the development of the RMF and the expert interviews regarding the specific thematic issues regarding resilience and governance.

Denscombe (2007) outlines the key decision factors for case study development on which the success of the research will depend, including a clear question to be answered and a link to sufficient data. In addition, Denscombe (2010) reasons that this decision process should be based on the individual characteristics of a particular case study: the choice is made to advance understanding of the external issue. In order to identify suitable cases, the case selection focused on identifying an advanced city, with modern STS and from which data could be gathered. The European Union (EU) FP7 and H2020 projects were influential here as access to experts and practical examples of tools from across Europe were made available.

Pan and Tan (2011) put forward an approach which meshes case findings and theoretical interpretation in the results section, deviating from more traditional approaches that advocate the separation of theory and data. This enhances efficiency and comprehensibility as it removes the burden of connecting the theoretical points of a conventional case description section, where data is presented without theory. Yin (1981) acknowledges that the success of the case study is dependent on a clear conceptual framework, in this case the RMF. Furthermore, a feasibility study narrative may be replaced by a series of answers to a set of open-ended questions. In answering the research question (RQ4) put forward above, a major goal of the research is to ascertain whether a resilience framework for the assessment of STS can be developed and operationalized.

3.3.4 Overview of required information

The research design and strategy depends on obtaining information to satisfy the research questions set out in Chapter 2.

RQ1. How are resilience analysis strategies currently being employed in conjunction with STS?

RQ2 How can the resilience of STS be determined?

RQ3 How can STS be managed to reduce vulnerability to multiple hazards, increase capacity to tolerate and deal with change, and so achieve regional urban resilience?

RQ4 Can a holistic resilience framework for the assessment of STS (in an Irish context) be developed and operationalised?

This process begins with a series of further questions: What assumptions do I make about the information required? What information do I, the researcher, need to find out about the topic? What information is required by potential end users of the research output? What type of information is needed to perform analysis of the case study? What is the source of this information? The answers to these questions depend on the context, the purpose, and the scope of the research, and the main aim, problem addressed and research questions. I elaborate on these questions through the following paragraphs.

End Users

In attempting to identify the information needed, the usability for end users was a primary focus. The information required by potential end users including council management, academics, and/or lay citizens was judged based on the researcher's past experience of policy work regarding risk analysis in Ireland, and informal discussions with colleagues and acquaintances. Further, specific questions were designed specifically for the expert panel consultation during the study and the information sought here is reflected in the questions.

Analysis Requirements

The type of information needed to perform the case analysis includes the observable facts, written materials, data sets, geographical representations, opinions, and historical background relating to the case. These information sources provide the basis on which analysis can be performed. While in the first instance quantities measuring the resilience levels of urban systems are the priority (through the Disaster Resilience Indicators (DRIs)), this must be validated through qualitative means (expert interviews). It was therefore decided that adequate information could be obtained from the opinions of informed individuals who could validate the RMF through their understanding of current CI operations and the demonstration through the case study.

Information Sources

This research is focused on a single case and bounded unit of analysis in the form of STS in Dublin. Therefore, the most appropriate sources of information are quantitative data to inform the DRIs, sensor data from the STS case and individuals with identifiable expertise, that is, experts with relevant knowledge. Information for the case study may come from secondary sources including refereed academic journal articles, publications of relevant actors (non-refereed), and statistical information (primarily from government sources such as the CSO) and maps of the case area (including risk maps). The experts to be interviewed may include academics, engineering management practitioners and policy makers. Expert opinion will be the one of the sources of information and the primary validation of the research. This leads to a justification of the selection of expert opinion as the source of information for this research.

3.3.5 Expert opinion

The expert opinion specifically addresses RQ4 in order to test the practicality of the RMF. Increasingly, expert opinion is being recognised as a valuable information gathering method for decision making and management. Through the literature the terms “expert knowledge”, “expert judgement” and “expert opinion” are used interchangeably. Local knowledge is a necessary means to contextualise and challenge common perceptions and general knowledge. Local experts include engineers, risk analysts, academic researchers, environmental managers, city managers and groups of experienced city stakeholders who hold knowledge and experience grounded in daily scientific practices (Krueger et al., 2012). Lay citizens or low-level system workers can also participate as data collectors, experts do not necessarily have to be at the head of organisations involved in the case. Modern science is often solely focused on the opinion of senior experts and so more traditional knowledge forms from workers directly involved with the system daily can be marginalised (Chan, 2013). Collaborative approaches to decision making emphasise the value of taking a range of perspectives into account as part of data gathering (Arnold et al., 2012). Furthermore, Krueger et al. (2012) explain that throughout the expert elicitation literature, the term “expert” has come to mean anyone whose opinion might be of interest. An expert can be pragmatically used to describe anyone with extensive knowledge or experience to the subject matter. Experts should be selected based on criteria that reflect this expertise (Azadi et al., 2007).

Martin et al. (2012) explain expert knowledge as substantive information on the research topic that is not widely known by others. An expert is the individual who is deferred to in the interpretation of events and occurrences within the system. Three types of expertise are identified:

- (i) Substantive - which reflects knowledge of a domain;
- (ii) Normative - which is the ability to accurately and clearly communicate judgements; and
- (iii) Adaptive - which describes the degree to which one is able to extrapolate or adapt to new circumstances.

Furthermore, when experts use their unique knowledge to make predictions about the system this is referred to as an expert judgement. (Martin et al., 2012).

Expert opinion is a legitimate source of information for decision and analytical modelling where required data, such as management decision making processes or system data, may not be publicly available and would otherwise be difficult to obtain (Leal et al., 2007). Kueffer et al. (2012) explain that standard research methods are unfit for the complexity of resilience problems, which regularly span broad spatial and temporal scales. Alternative approaches are required to address issues involving resilience and complex STS, this includes how data is gathered and how to determine the validity of results. Often the data or information available on complex STS is limited and expert opinion offers substantial information that would otherwise be impossible to obtain from the data, and may fill in the gaps where processes are vague, or data is unavailable (Dorussen et al., 2005). System analysis requires methods of evidence rationalisation, “*eliciting expert opinion and evaluating consensus between experts is one such approach that has been shown to lead to balance informed decisions*” (Jones et al., 2013).

Expert Panel Selection

The development of appropriate criteria for expert panel selection will guarantee the quality of expert knowledge. These experts must be capable of giving insight into the case (substantive), rigorously analyse the proposed resilience tools (adaptive) and be capable of expressing opinions regarding the case generally (normative). Cooke and Goossens (2004) recommend that experts are selected based on their professional

reputation, this would take into account their experience in the field and publications in the area, or other award and notable distinguishing factors. Eliciting expert perceptions considers individuals who, having specialised in their particular area of work or research, have extensive knowledge of the issues. Experts should be identified according to a specific set of criteria; studies with a high degree of uncertainty and complexity, such as STS, require a wide range of disciplinary input (Lowe and Lorenzoni, 2007).

McLeod et al. (2015) selected vulnerability and adaptability experts to participate in survey using the interview and focus groups in their study on the effects of climate change on tropical island communities. They selected experts based on the following criteria:

- (i) Knowledge concerning the topic as demonstrated by publication in peer reviewed journals;
- (ii) Research projects carried out on the subject area;
- (iii) Development of tools to measure and address the impacts of climate change; and
- (iv) Expertise in local community environments.

In addition, selection aimed to ensure a geographic and gender balance as well as finding participants who were eager to partake. Based on these criteria, 13 participants agreed to take part in the interview process (McLeod et al. 2015).

In another study Cornelissen et al. (2003) based their expert identification on the following two criteria:

- (i) The individuals experience or education in a specific domain; and
- (ii) The specific circumstances in which this experience is gained, i.e. in theoretical or practical circumstances.

While they did not put forward an extensive list of criteria, the important contribution is that the basis for expert selection must be transparent.

It is important to note that there is an important distinction between experts and stakeholders in case study research. A “stakeholder” may be an employee who has worked within a system for an extended period, but if this experience is not related to the case they would not be considered as an expert. The distinguishing feature must be

that experts are selected on the basis of proven knowledge supported by relevant selection criteria (McLeod et al. 2015).

3.3.6 Elicitation

Expert elicitation is a formal heuristic process of gathering information and answering questions on issues or concern (Ayyub, 2001). It is important to recognise the strengths and weaknesses of the various methods that exist to elicit expert opinion (Lowe and Lorenzoni, 2007). These different methods of elicitation can lead to differing results, and indeed so too can the analysis of these opinions by the researcher. This means that explicit justification for the elicitation design is crucial to overcome existing limitations (Krueger et al., 2012). In order to overcome these limitations expert elicitation should be:

- (iii) Reproducible, documented for peer review;
- (iv) Accountable, where possible participant experts should be named;
- (v) Controllable, confirmed by other information sources;
- (vi) Neutral, in terms of the conduct of the elicitation process; and
- (vii) Fair, with each expert should be treated in the same way (Krueger et al., 2012).

The type of information sought will dictate the elicitation procedure. Individual or group elicitation strategies have different benefits; individual interviews allow for direct targeted questions and feedback, but can be limited by the preconceived ideas of the interviewer. Group discussion allows for a greater sharing of knowledge, but can lead to group think and conformity due to a perceived need for consensus. Individual elicitation also allows for standardisation and by briefing beforehand, individuals will be more attentive and sincere in their responses. This may not occur to the same extent in group interviews (Krueger et al., 2012).

In an attempt to avoid the disadvantages associated with the more conventional use of experts, such as group discussions and brainstorming exercises, an individual interview approach was selected. This is more conducive to independent thought and allows time for considered opinions to develop. Group discussion can lead to defensive stances taken on preconceived opinions or, alternatively, opinions can be swayed by more vocal

group members. A systematic approach is required that allows for the exploration of all aspects of the topic and to establish whether any theoretical assumptions or misconceptions on empirical factors which may have been overlooked (McLeod et al., 2015).

Among the most popular elicitation strategy is an unstructured interview method. This method aims to obtain the most reliable consensus of opinion from the expert panel. Intensive interviews are used to elicit information. Focussing on a central problem, the questions aim to identify the expert's rationale, the factors relevant to the problem, the importance placed on different aspects, and what kind of information would be needed to improve their decision making capability. The initial information used to lead the questions should take the experts into consideration (Dalkey and Helmer, 1963).

As with any elicitation methods, considerable discretion must be exercised by the researcher as to the information introduced to the expert before or during the question process to ensure that bias is minimised (Dalkey and Helmer, 1963). This and other potential instances of bias in the research are explored in the next section.

3.3.7 Dealing with bias and ensuring validity of results

Expert opinion is susceptible to a range of subjective and psychological bias (Martin et al., 2012). Individual bias and perspectives can often unknowingly influence expert opinion. These biases are difficult to remove, therefore effort is needed to identify bias and make them explicit where possible (Cornelissen et al. 2003). As expert opinion is often used for specific case examples, researchers must be careful in making wide-reaching conclusions based on their input - contextual bias is a valid criticism of using information derived from expert opinion (Martin et al., 2005). This presents a challenge in how the elicitation process is approached. The interview method used through this research aims to minimise this bias where possible.

Despite the potential for bias, not all experts in the elicitation process will be biased. Furthermore, bias may be mitigated through careful management and the crafting of questions and feedback that are aligned for specific experts. Some biases, which are outlined here, are harder to mitigate:

- (i) Overconfidence bias is the unfounded belief of the expert in validity and accuracy of their statements;
- (ii) Motivational bias arise where the expert has a personal stake in the case or the desire of the expert to answer questions positively as they relate to their profession or employer;
- (iii) Accessibility bias occurs where information that is more easily accessible or available to the expert becomes the basis of the experts judgement; and
- (iv) Anchoring bias occurs when an expert relies too heavily on an initial reference point and is unable to adjust their view despite new information to the contrary (Lombard et al., 2010).

These biases may be minimised by including a wide range of experts across a range of professional backgrounds (Lombard et al., 2010). Furthermore, experts have been found to express views beyond their own area of expertise where too much scope is given in the questions, as an overconfidence bias, however, this can be mitigated with specific questions designed to address the research topic only (Bray and von Storch, 1999).

Expert judgement depends on its consistency in quality across time and situations. The validity of the expert elicitation will depend on its relevance to the case in question. Expert opinion depends on and is validated by the reputation of the experts selected, however even where experts are chosen specifically for a case it may be necessary to review and discount particular answers given where bias is detected (Dorussen et al., 2005).

Validity of expert opinion may be updated to reflect changes in expert judgement as new evidence becomes available. Therefore, their opinions should be documented in such a way so that answers can be revisited and updated as necessary (Martin et al., 2012). Validity may also be improved by consulting multiple experts on particular topics to ensure a range of views are recorded, ensuring anonymity between experts, and having clear communication with experts:

- (i) There is no ideal number of experts for studies of this where expert opinion is needed (Powell, 2003). It is noted that interview studies generally range from 10 to 35 people (Gordon, 2009). Avella (2016) noted that panels should not be smaller than 10 and should be large enough for differing views to emerge. The panel should remain small enough to enable the research

team to administer the project and turn the questionnaires around in a timely manner. Panel sizes may vary depending on the scope of the problem and the available resources (Powell 2003). The size of the panel is not as important as the expertise and background of the experts to cover the critical aspects of the research topic (Avella, 2016).

- (ii) Anonymity between panellists is a significant issue and, at the very least, panellists should not be together when questions or interviews are taking place. Individual interviews reduce the negative influence of peer pressure and the bias of having dominant personality types who can lead groups in a particular direction. Furthermore, junior staff are unlikely to contradict their superiors. Controlled methods such as the Delphi technique allow expert views to be presented in such a way that the individual can remain anonymous and so make them more likely to be honest in their responses (Rowe and Wright, 1999). Sackman (1974), however, notes that anonymity may lead to the abandonment of accountability and the reinforcement of elitist interests, and additionally, experts may be unwilling to become involved in the first instance if their input is not acknowledged. The researcher must control the degree of anonymity at different stages of the research process, at the design stage brainstorm and group exercises may be useful to bring creativity, however, the validation stage of an interview process will require a greater degree of anonymity.
- (iii) Implicit in the process of expert elicitation is the need to establish a setting in which experts can discuss the topic and interact with the researcher and the research material. A structured interaction should be prepared by the researcher and adapted to the personal requirements of each expert separately. Where face to face interviews are unfeasible, online communication may suffice but should be seen as a secondary option. Any communication with the experts should be reviewed to ensure that only such data as have been asked for by at least one respondent and are obtainable and reliable should be shared with all of the experts (Dalkey and Helmer, 1963).

3.4 Methods

This methodology is the conceptual pathway for the development and feasibility testing of the RMF: an initial theoretic proposal, which was then tested technically, organisationally and through expert interviews all in the context of the Dublin Water system.

The methods section outlines the systematic procedures adopted to accomplish the research objectives. Methods are the practices and procedures adopted by the researcher at both a theoretical and practical level to answer research questions and to achieve the research objectives. This section outlines the methods and tools used in this research, including the RMF tool design, expert panel, and data analysis. At this stage it is important to understand the research process and steps taken to develop the RMF, Figure 4.1 below outlines the main components of this research.

The development of the first RMF draft was informed by the literature review and work carried out by the researcher on EU research projects. This initial draft was then presented at an IRSPM conference and underwent academic peer review. The feedback from the peer review was addressed and the initial testing of second draft of the RMF in the case study could commence. Feedback from the case study led to ongoing updates to the RMF through the study period. Further feedback was then received from the expert interview which informed aspects of the case study as well as a further review of the RMF itself. The feedback and analysis of the case study results were incorporated in the final draft of the RMF presented in Chapter 4.

3.4.1 RMF Development

Overall, this research aims to further advance the state of the art of urban resilience management and intends to increase and optimise the uptake of resilience measures by a range of stakeholders across academia, city management, and infrastructure service providers. Merging the concept of STS with urban resilience theory and their application in the case study demonstrates how research can move beyond the existing state of the art to facilitate the operationalizing of urban resilience.

How to measure resilience has been addressed through management frameworks, indicators, and case studies through the scientific literature (Hosseini, et al., 2016). These tools, however, are often conceptual in nature or at the stage of early proof of concepts. This chapter will identify the methodological approach used to move resilience from a conceptual understanding to a practical and operational management framework. This framework integrates the best practices across current resilience thinking, risk analysis and management approaches. As part of this research, an RMF is developed. This framework aims to support the practical application of resilience to communities and the CI systems that support them.

Key components of the RMF are a set of resilience indicators that will enable urban systems to have their level of resilience quantitatively and qualitatively indexed. These indicators will allow for the quantitative analysis of the resilience of the urban system across different spatial scales across Ireland, including the city, county, province and national scale. This information can then be used to direct users to aspects of their systems where resources could be concentrated in order to further improve their resilience levels. The RMF and associated tools were partially tested and validated through stakeholder engagement, table-top exercises and a large scale case study of Dublin. The RMF also consists of learning and educational material that provided further guidance and training on urban resilience for the stakeholders.

The development of the RMF was an iterative process of incorporating different management approaches, methodologies, standardised tools, which were reviewed in Chapter 2; these included the European Risk Assessment Guideline and relevant supporting tools. The Employment Based aspect of this research played an important role in the development of the draft RMF which was subject to initial testing through the case study involving the Dublin City Council led Internet of Things (IoT) Flood Research Consortium and the Dublin Smart Docklands initiative. Input from these stakeholders both in terms of current practices, data availability and which were used to refine the RMF.

In working with practitioners and colleagues on resilience projects on a daily basis, it became apparent that a ‘one size fits all’ approach in terms of trying to research and develop resilience measure to address any disaster event type would be impossible. The

research project outputs would be too general and have limited applicability to real world scenarios. The decision was made to develop urban resilience tools to address the most common threat in Ireland, which is the increased level of flooding caused by climate change.

3.4.2 Case Study Approach

The research aims to develop and trial professional approaches to embed resilience within design processes through an empirical contribution with the development of a RMF. This framework aims to provide decision makers with a baseline measurement of STS resilience and suggests how resilience capabilities may be improved. The framework is tested with a case study which helps to develop practical pathways to resilience attainment. This case is designed as a multi-stage, multi-method case. Following the case, conclusions are drawn deductively from expert interviews.

Based on the selection process analysing access and the availability of data, a city-wide STS system was selected as the unit of analysis with service provision acting as the dependent variable (Eisenhardt, 1989). A finite time period of 2000 to present was selected due to the significant technological advances made in the last 15 years, which directly affect STS resilience. This approach was adopted due to the critical realist perspective; unobservable structures cause observable events and the social world can be understood only if people understand the structures that generate events. Therefore it is important to understand the structure of the decision making bodies, but also to capture the understanding the key agents have of these same bodies.

Rather than juxtaposing several city cases, it was decided that an embedded case in one city would enable better analysis of the RMF and its application to the STS. Due to its proximity, availability of information, access to experts, familiarity of the research and as an advanced city with modern infrastructure systems, Dublin city was selected. The primary system to be analysed is the water infrastructure system inclusive of the water supply and grey water management processes for the city.

Resilience management is generally concerned with multiple unknown threats that cannot be predicted or foreseen. Due to limited resources, a singular threat was chosen. In Dublin the main natural risk to the city in the coming decade is flooding (Office of

Public Works (OPW), 2015). For this reason the research focuses on improving the resilience of the STS to flooding in Dublin.

Data collection focuses primarily on printed materials, documents from archival sources, and expert interviews as discussed above. Initial investigations and discussions with RESILENS project partners confirmed that data would be accessible, in some instances colleagues were able to suggest and provide additional data sets which would not have been available to the general public such as the waste water system pipes map and existing sensor data. In addition to textual materials identified, interviews are also be possible. Furthermore, contacts in DCC, Irish Water, OPW, Smart Dublin and academic contacts in Trinity Haus and the Trinity Connect Centre may be exploited. The availability of these contacts and data is facilitated by the nature of the Employment Based research.

This study outlined here is complemented by expert interviews which aim to elicit effective and practical approaches to the implementation of conditions for urban resilience. The study identifies sources of resilience and resilience dynamics that require management in the context of STS management. The thesis is concluded with a discussion on the importance of new professional tools for facilitating the delivery of resilient systems and with the conclusions of the study.

The main case study tasks are outlined here:

- (i) Establish the current state of the art (SOTA) regarding urban resilience policies and practice as they relate to STS currently in use in the literature. This task will necessitate a review and analysis of current resilience assessment frameworks and indicators.
- (ii) Identify previous relevant resilience frameworks and their shortcomings and limitations regarding their intended application for STS resilience assessment. Undertake a further review of the existing resilience policy areas and how they relate to the corresponding governance structures.
- (iii) Develop a functional framework for the quantification of STS resilience. This will necessitate an analysis of current best practice and adapting the appropriate tools for resilience analysis. Additional contribution to this analysis may include discussion with industry leaders.

- (iv) Developing and proposing functional indicators for the evaluation of STS economic resilience. Testing of the proposed indicators using fit-for-purpose analysis procedures (a case study) to ascertain their relevance for the intended framework, and suitability as useful resilience identifiers. Once baseline levels of resilience may be monitored the steps to improve resilience of the STS may be developed.
- (v) Combining the concepts developed in the earlier tasks in the application and testing of the RMF within the case study area. This task will involve the application of the RMF to the Dublin case study and testing its validity through engagement with a range of built environment professionals, academics and policy experts in the form of interviews and consultations.

3.4.3 Expert panel

In addition to the literature review, the expert interviews with engineering practitioners working in urban environment is a necessary research component to gain further understanding as to how resilience is interpreted in current practice, validating or discounting the literature, and to understand the practical issue impacting on resilience in their daily work.

The design of the RMF is based on ad hoc and semi-formal individual and team meetings and before the final validation interviews which involved a series of formal one-on-one interviews.

This research has the stated objective of making a theoretical contribution to the urban resilience literature and to produce practical insights for its implementation expert opinion from industry leaders can provide important insight for both of these purposes.

Expert selection

The selection of experts for the interview process, as detailed in Chapter 5, is based on the following criteria:

- (i) Years of experience in STS management or related disciplines;
 - (ii) Active involvement in research, policy making and professional organisation;
- and

- (iii) Central figures in local government, service providers or relevant stakeholder organisations.

These criteria ensure that interviewees are selected and exposed to current professional standards. The opinion of these experts helps to consolidate the finding from the literature review and to shape the development of the RMF. The analysis of these interviews will include a thematic analysis, which aims to report patterns or themes within the data. The interview questions are compiled to reflect the research questions, focusing on the application of urban resilience theory to STS in practice. From the literature, there is a clear need to bring clarity to the concept of urban resilience, which has a number of broad definitions across research disciplines (Hosseini et al., 2004). Moreover, the issue of how to apply this concept in practice leads directly to questions around measurability and a focus on the validity of the proposed DRI. Further details of the process leading to the interviews are detailed in Section 3.5 below.

The list of questions is sent to each of the expert interviewees prior to the interview itself. This allows time for the experts to reflect on the questions and to give a more in-depth answer. Although the questions aim to analyse the same topic, the questions may be adapted depending on the role and experience of each expert; the questions will remain as similar as possible for each topic under review.

This section describes the interview process from design to implementation held with decision makers, practitioners and academics with knowledge of flooding and resilience in Dublin, Ireland. The interviews were conducted so as to ascertain if, and how, resilience is understood and is being applied in flood management currently within the interviewees' area of competence, and the feasibility of an RMF. Much of the theory-based resilience information has been gathered through the literature review, and so the interview process has a more refined function of analysing key aspects of the RMF and answering how the RMF may be applied in practice to the Dublin case study. The questions themselves were developed through an iterative and reflexive process of reviewing the academic and practical literature on questionnaire design (Rowley, 2014) and a pre-case test with a research expert in the field.

This leads to the question of how to select interviewees that will provide reliable and accurate information in order to answer the questions outlined. The method used,

known as the knowledge resource nomination worksheet (KRNW), is a procedure for selecting qualified expert practitioners in line with the guidelines provided by Delbecq et al. (1975) in relation to a nominal group study technique. There are, of course, numerous people with knowledge concerning the resilience and various aspects of flood management in Dublin. Indeed, any citizen or habitant of a city or connected to the macro-region, in this case Leinster, and even Ireland generally, may have knowledge of the case area. However, this research focuses on the case study and analysis of the water infrastructure within the study boundary of the DCC municipal area. Therefore, the appropriate sources of data for this case are people with demonstrable expertise and experience such that they may be identifiable as an expert in the areas of resilience and/or flood management. These experts may consist of academics, or non-academics, elected officials, water management experts or a mixture of these. Expert opinion is an additional source of data in terms of verifying the validity of the RMF and the case study. The KRNW is a detailed step by step process which addresses the purpose of the interviews to gather opinions from academics, those involved in the political sphere, and engineering management practitioners on urban resilience (detailed in Figure 3.2).

In order to elicit the key issues with regard to the case study (including the study area, the STS context, the application of the RMF, and the potential challenges therein), it is necessary to identify a group of experts who are experienced, knowledgeable and capable of expressing their opinions on the research area. Cornelissen et al. (2003) distinguish between the role of stakeholders and experts, where the former has an interest in the study area but may not have the necessary experience to be considered an expert; stakeholders and experts are selected on the basis of different criteria. Although there is no definitive list of criteria for expert selection, experts may be differentiated from stakeholder by their knowledge and experience. These selection criteria should be based on the reputation, experience, publications and positions held by the expert candidates in the area under study (Cooke and Goossens, 2004).

The criteria for expert selection should be based on the experience the person has in a specific domain of knowledge and the circumstances of this experience, which may be theoretical or practical (Cornelissen et al., 2003). A candidate's experience may include their work in a specialised area, demonstrated by their participation on a particular project relevant to the research area (Lowe and Lorenzoni, 2007). For complex research

areas, such as sustainability or resilience where interdisciplinary approaches are prevalent, these different areas of expertise should be reflected on interview panels by including a range of disciplinary inputs. This approach allows experts with a diverse experience and research background to work together to address issues around climate change (Lowe and Lorenzoni, 2007). For their infrastructure resilience study, Chang et al. (2014) selected organisational specialists to participate in interviews. Their selection criteria were based on the professional role held by the expert within infrastructure organisations alone.

Through this study, the researcher compiles expert knowledge on the main issues facing water infrastructure and communities in Dublin, resulting from flooding and how to mitigate the impacts of this. The researcher obtains this knowledge through data that is gathered from interviews with experts. This involves collating the insights of these experts across a range of disciplines, from academic researchers, policy makers, and infrastructure management, and integrating these into a coherent whole. Given that the data collected will be in the form of expert interviews, in order to be able to draw conclusions from these it is necessary to form the experts into a panel for consultation.

The expert panel design depends on the information that is required, therefore before selecting the panel the questions to be answered should be defined; see Appendix B for interview questions. The interview questions are designed to address areas where limited data is available and expert knowledge is needed in order to successfully test the RMF to the local context. The questions address general themes, including the geographic study area, the social and political context, the main threats in the area and, without asking explicitly, how the expert currently understands or applies resilience. The questions probe how this concept is understood within the different professional domains, how the application of the RMF to the water management system in Dublin can be achieved and how resilience can be measured and improved through the use of the RMF and specifically the DRIs.

The systemic approach to case study design requires consistent scales of intervention, which leads to initial questions concerning the spatial scales at which resilience should be examined (see section of the questionnaire: ‘Spatial boundaries’). Establishing the purpose/finality of a system helps identify risks of failure and therefore effective

strategies for resilience. In the case of urban STS, it is assumed that their ultimate purpose should be their sustainable state to provide for the citizens who rely on them. It is assumed that the resilience of this state is desirable. This leads to the question about the perceived relationship between the users and resilience management (see section of the questionnaire: ‘Social and political capacities’ and ‘Economic capital’). Finally, since this thesis aims at exploring practical applications of the concept of resilience in practice, a final set of questions are included that concern its measurability and applicability reviewing the RMF (see section of the questionnaire: ‘Socio-technical systems & resilience tools’). Various authors offer guidance regarding expert selection procedures (see, for example, Tolley et al., 2001; van Zolingen and Klaassen, 2003; Okoli and Pawlowski, 2004; Scapolo and Miles, 2006; Gordon, 2009).

This study does not depend on a statistical sample that attempts to be representative of any population; it is a group decision mechanism, requiring qualified experts who have deep understanding of the issues. Therefore, one of the most critical requirements is the selection of qualified experts, in order to ensure transparency in the selection process the KRNW process for expert selection was chosen. The KRNW selection process involves a multistep, iterative approach to identifying experts, summarised as follows in Figure 3.2:

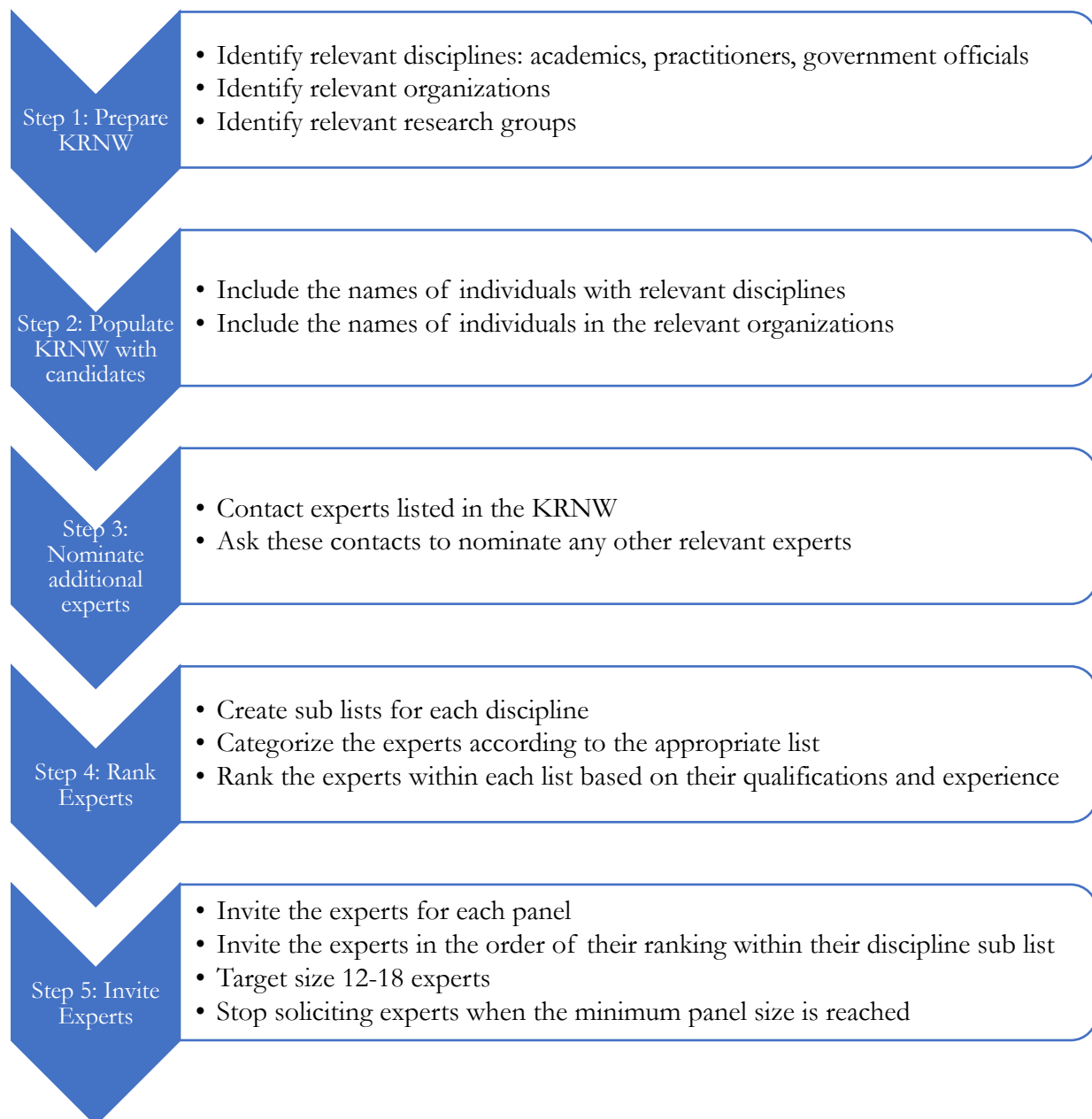


Figure 3.2. Procedure for selecting experts in the case study.

3.5 Qualitative research

The term expert is used to describe anyone whose opinion may be of interest to a study (Krueger et al., 2012). Any person with relevant and in-depth knowledge or experience of the topic may be considered an expert. An expert is one whose knowledge is built over a period of experience in a specific domain (Cornelissen et al., 2003). Here the definition suggested by Lele and Allen (2006) is used: ‘a useful expert is one whose opinion adds information over and above what is provided by the observed data.’ They may be selected based on criteria that reflect their knowledge and experience, and the

applicability of these for the research. These experts may have knowledge about various aspects of the research topic, including knowledge of aspects that may not be available to the general public, or of experience working in the field so as to understand the specific working and issues of the area. From initial informal discussion with DCC staff about flood management techniques, it became clear that much of the decision making process is based on the personal experience of the team, rather than data-based decision making. Scientific theory can be contextualised, and even challenged, by local knowledge, when applied to a specific local context (Krueger et al., 2012). The experience of the DCC flood management team and subjective opinion of this nature is considered to be a legitimate source of information for data collection where observed evidence is unavailable (Leal et al., 2007). This type of knowledge is subjective and must be taken in good faith that the expert is credible (Cooke and Goossens, 2004).

For certain research topics, where empirical information is scarce, expert knowledge may be the only form of information available. Expert knowledge can be collected in a relatively short period of time and it is inexpensive when compared to other data collection methods. Martin et al. (2012) explain that expert opinions may be the most credible source of information in the decision making process. In some instances where a problem is clearly defined and the key decision makers are easily identified, the required expertise is likely to be evident. Due to work carried out on the RESILENS project and later work with the DCC flood management team the dependence of the water management system on experience of senior engineers was clear. There was a lack of empirical evidence on which to carry out research in the first instance.

When dealing with the complexity of STS and urban resilience the required expertise may not be so obvious (Sherriff et al., 2014). The number, type, and selection process for experts and the elicitation process to gather their opinions are challenges when dealing with expert knowledge, which are explored in Sections 3.4.3 and 3.6. Some of the main issues include expert bias in their judgements, self-serving opinions and researcher bias, any of which may lead to low-quality decision making (Jordan and Javernick, 2013).

3.6 Expert Elicitation

Expert elicitation is the systematic approach to gather and synthesise the unpublished knowledge from experts in order to create explicit and usable information (Jordan and Javernick, 2013). The primary elicitation method for expert opinion is the interview, however this may take a number of forms. Interviews conducted in person, by phone, or over conference call, such as Skype, are preferable to survey style interviews. Without interpersonal contact, implicit information may be missed and the given answers are more open to interpretation. Furthermore, face-to-face interviews allow the researcher to ask follow-up questions or seek clarification of answers where necessary (Frechtling, 2002). The limitations associated with expert elicitation can generally be overcome with clear justification for decisions around the design and documentation of the elicitation method (Krueger et al., 2012). Lowe and Lorenzoni (2007) illustrate the benefits and limitations of the various methods available to elicit these views and explain that different elicitation methods may result in different results. The three principal individual interview techniques are:

1. **Structured interviews**, are uncompromising in how they follow identical questions and formatting to each interviewee, the researcher must ensure the questions are asked in the same manner and minimise deviation from the questions given;
2. **Unstructured interviews**, are built around open-ended questions that allow the researcher to guide the conversation to allow for open, detail-rich responses; and
3. **Semi-structured interviews**, are a hybrid format, which aim to balance the structure of structured interviews and the flexibility of unstructured interviews. Semi-structured interviews are similar to unstructured interviews in that they aim to elicit detailed material from the interviewee, which can be used for analysis, but they are more structured in that the questions follow a specific order while allowing for follow up or expansionary questions (Lowe and Lorenzoni 2007).

In order to address the research questions (RQ1 and RQ4) and the stage of the research in terms of the development of the RMF necessitated that the interview be either unstructured or semi-structured in nature. The structured interview was deemed too rigid to allow for open responses from the experts. Furthermore, the structured

interview could prohibit the inclusion of any response specifically asked in the questions but which may be important to the expert and, indeed, for the topic. The unstructured and semi-structured interviews allow for a more conversational format, which gives the researcher flexibility to explore any areas of interest as they arise. Too much flexibility can lead to perception errors and inconsistencies across interviews, with too large a volume of information to allow for the elicitation of accurate or relevant information. The semi-structured approach was seen to be most appropriate due to the need for clarity around specific areas and in order to maintain a standard format across the interviews so that common themes could be identified. For each interview an audio recording is made, which is transcribed and augmented by hand written notes taken by the interviewer during the interview process. In order to reduce the inhibition of the experts induced by being recorded, they were made aware of this in advance of the interview. Consent for the audio recording was sought from each candidate as they confirmed their participation, see Appendix C for a copy of the consent form that was signed by each participant.

3.6.1 Dealing with bias and securing validity

As both the facilitator of the interview and data analyst, the researcher's personal views can bias the group process (Krueger et al., 2012). The limits of the study, the subject matter, and the interpretation of data was filtered through the researcher's perceptual bias. This issue manifests itself in the conceptualisation of the RMF, details of which were presented to panellists during the interviews. As a single researcher, other forms of bias including geographical (the selection of Dublin, an area the researcher is familiar with) may have had an effect in terms of applying geographical selection criteria when identifying candidates to form the expert panel. For example, the panellists are all based in close proximity to the study area; this was a deliberate decision as the study aimed to elicit the opinions specific to flood management in Dublin.

One of the main criticisms of using the expert opinion in research is the fact that experts may carry with them a bias based on their context (Martin et al., 2005). The opinions being captured through the expert panel are subjective and may be susceptible to unconscious or conscious bias (Martin et al., 2012). Despite the potential for bias, not

all experts will display bias and the potential for bias can be mitigated by careful management of the interview process, including clarification around what is being asked, and the provision of clear unambiguous feedback (Martin et al., 2012).

Individual bias and personal views can influence the most objective experts and so their output may not be wholly impartial (Hallowell and Gambatese, 2009). Localised knowledge may be biased by different backgrounds and experiences; given that the aim of this study is to elicit this knowledge and draw conclusions from it presents a challenge in how the expert elicitation procedure is designed. Martin et al. (2012) identified four common types of bias as outlined. Firstly, motivational biases arise from the context of an expert's personal beliefs and from the personal stake he or she might have in a decision. Secondly, accessibility biases arise when information that comes more easily to the mind of an expert exerts a disproportionate influence on an expert's judgments. Thirdly, anchoring and adjustment biases occur when an expert relies too heavily on an initial piece of information or familiar reference point or 'anchor' to make subsequent judgments and is unable to adjust their view from this anchor. Finally, overconfidence bias can arise when the confidence of an expert in his or her judgments is higher than is warranted by the accuracy of their estimates. (This may be the most challenging to mitigate.)

Dorussen et al. (2005) conclude that in order to secure validity, that there are good reasons for consulting multiple experts to increase the validity of the data. The issue of anonymity in terms of allowing panellists to answer the questions free of social pressure or the possibility of confrontation is significant. Where at all possible, interview candidates should be interviewed individually so as to avoid 'group think', which is shown to be inferior to individual responses (Postmes and Lea 2000). Panellists in group interviews may consciously or unconsciously succumb to peer pressure or bias arising from the presence of a dominant personality or more senior panellists (Powell, 2003). Naturally occurring social processes may negatively impact the quality of decision making in groups and should be avoided by conducting interviews on an individual basis where possible, this will provide responses more reflective of each individual's personal opinions (Landeta, 2006). By including a number of experts across knowledge areas, in different organisations, and interviewing them individually, where possible, most of the possible biases can be mitigated (Lombard et al., 2010).

3.6.2 Panel Size

Studying resilience on a city wide level will require a panel size that is manageable, so that responses can be analysed in a timely manner, but that is simultaneously large enough for differing views to emerge among the panel members. Expert panels are not reflections of opinions of the general public, and so the panel size is not required to be statistically significant. There is no consensus on the required number of panellists for studies (Powell, 2003). Hallowell and Gambatese (2009) recommend between 8 and 12 panellists for an effective panel. In their 1975 paper, Delbecq et al., suggest that a minimum of 12 up to a maximum of 18 panellists are required. The average study using the Delphi method has panels of between 15 and 35 (Gordon, 2009). Larger macrorregional studies may necessitate larger panel sizes, for example, in their 2013 flood risk study, Lee et al., interviewed 44 experts.

Powell (2003) suggests that the panel size will depend on the scope of the problem, the research timeframe, and the available research resources. Although the geographic area being studied is significant, the number of experts in relation to flood management in Dublin is relatively small. The main factor in deciding the number of panellists is that the panel is balanced in terms of the disciplines and experience of the individual experts. Based on these factors, and in keeping with the method described by Delbecq (et al., 1975), it was decided that a minimum of 12 panellists and up to a maximum of 18 panellists would be required for an adequate panel for the study.

3.6.3 Invitation list

The selection of candidates for the expert panel followed the step-by-step selection process outlined in the KRNW sheet, before individuals were contacted and invited to participate in the interviews. Gordon (2009) suggests that the potential candidates will have an acceptance rate of between 35% and 75%, this should be factored into the initial contact invitation list. The number of experts required for the panel may vary depending on the elicitation method chosen and/or the need to account for potential low acceptance rates. In some cases the initial contact may themselves be unavailable for interview, in this case they may nominate another expert or experts in their organisation who may act as a substitute panellist. Although the initial interview invitation will not

include a request for a substitute, in the event of an invitation being declined, a follow-up email will be sent to request the candidate to nominate a suitable substitute. For the purposes of this research, the nomination of a substitute expert will be considered a valid peer recommendation. The invitations were generally received with the majority of responses being straight forward acceptances with candidates agreeing to the interview. In the cases where candidates did not reply a follow up email was sent. Therefore, the request for substitutes was not necessary. During the interview proper, Cllr. Dermot Lacey suggested that I contact Senator Kevin Humphreys, who was already on the list of candidates.

The first step in the preparation of the KRNW is the identification of experts' classes under the categories: disciplines or skills, organisations, and related research. In short, the selected experts consisted of three core groups:

1. **Academic:** researchers from relevant EU research projects with experience of applying resilience in Ireland;
2. **Political:** Elected officials across all levels of government responsible for flood management policy design and implementation; and
3. **Engineering Management Practitioners:** Managers from civil bodies responsible for flooding in Dublin.

Therefore, the strategy used was based on my personal knowledge, experience and searches to identify practitioner candidates, including policy experts, by first identifying the relevant organisations, programmes or projects with which are associated with flood management. This involved personal brainstorming to produce an inventory of organisations and institutions that have some relationship with the subject areas relevant to the study. The purpose was to identify as many relevant organisations and institutions as possible; that is, relevant in terms of their 'proximity' to issues concerning water management, flood risk analysis, and flood mitigation in Dublin.

3.6.4 Communication

Concerning identified organisations, the objective is to contact people in these organisations who are experts themselves, and who can provide additional contacts within and outside their own organisations. The KRNW is then populated with names of potential experts under each category, starting with a personal list of contacts before

applying Delbecq et al.'s (1975) procedure to ensure identification of the most qualified experts. The same names may appear under more than one category throughout the KRNW. Next, the identified experts are contacted and asked to participate in the interview process or to nominate others for inclusion on the list.

Initial contact and the invitation to participate in the interview was made via email in each case. In terms of the interviews themselves, the face-to-face interpersonal communication is a vital component of the study design in order to better understand any social queues or implicit communication beyond the explicit verbal responses. Throughout the process of expert elicitation, there is a need to establish a setting in which geographically dispersed panellists can interact with the researcher and the research process and, in this case, not with each other. This structured interaction will take place in the interview candidate's office or, where this is not possible, in a neutral venue. In this case, the candidates who took part in the interviews were not geographically dispersed, and so, carrying out the interview in person was not cost prohibitive. All of the interviews (with the exception of one phone interview with Cllr Paddy McCartan), were carried out in person.

The experts are ranked according to the person's role, their years' of experience and the person degree of qualification. Based on the rankings, the experts are invited to participate in the study, stopping when the minimum required panel number, 12, is reached. An example of the working KRNW is shown in Table 3.1:

Disciplines or Skills	Organisations	Individual Experts
Academic Researchers	TCD (RESILENS) UCD (OPERANDUM) NUIM (ICARUS)	Dr Ehiaze Ehimen Dr Francesco Pilla Dr Maria Nogal Dr Conor Murphy
Management Practitioners	Office of Public Works Irish Water Dublin City Council Smart Dublin Met Éireann Environmental Protection Agency	Mr Gerry O'Connell Mr Alan Vickers Mr Bill Nolan Mr Mark Adamson Mr John Murphy Mr Jamie Cudden Mr Michael Guerin Mr Dick Gleeson Mr Alan O'Rourke Mr Eoin Sherlock
Policy Makers	Dublin City Council Seanad Éireann Dáil Éireann	Mr Kevin Moran TD Senator Kevin Humphreys Cllr. Dermot Lacey Cllr. Claire Byrne Cllr. Paddy McCartan

Table 3.1 Knowledge Resource Nomination Worksheet

The selected candidates were contacted by email with an invitation to participate in the study. These contacts are provided with a brief description of the study and explanation that they have been identified as experts on the subject with knowledge of the case area. This included a statement of the study objectives, requirements of panellists, the questionnaire and consent form. Two weeks later, a reminder was emailed to candidates who had not yet responded. Copies of the questionnaire and consent form are presented in Appendix C. Of the initial 20 candidates who were contacted 13 agreed to take part in the interview, an acceptance rate of 72%. A summary of the candidates, their associated bodies, and their relevance to resilience and flooding in Dublin can be found in Table 3.2. (The grey highlights on the table indicate candidates who were invited to partake in the interviews but declined or did not respond to the invitation). The

particular position within organisations and the professional experience of the interviewees displayed in the third column ensure that their opinions are informed, and to an extent, reflect those of their organisation. Their comments reporting professional attitudes on urban resilience and the application of the RMF to the case area are therefore considered by the author sufficiently reliable.

No	Candidate	Associated Body	Relevance to the study area
1	Dr Maria Nogal	Trinity College Dublin	Resilience Academic Researcher, RESILENS member
2	Dr Ehiازه Ehimen	Sligo Institute of Technology	Resilience Academic Researcher, RESILENS Project manager
3	Mr Bill Nolan	Irish Water	Risk Management Specialist, RESILENS member
4	Dr Francesco Pilla	University College Dublin	Resilience Academic Researcher, OPERANDUM Project manager
5	Mr Michael Guerin	Smart Dublin	Smart City Manager, Smart Dublin Flood Project
6	Mr Alan Vickers	Dublin City Council, Water Management	Chief Technician (Engineer), Smart Dublin Flood Project
7	Mr Alan O'Rourke	Dublin City Council, Water Management	Water Management Engineer
8	Mr Gerry O'Connell	Dublin City Council, Water Management	Chief Flood Engineer, Smart Dublin Flood Project
9	Cllr. Dermot Lacey	Dublin City Council, Councillor	Labour party, Representative of high flood risk area
10	Senator Kevin Humphreys	Seanad Éireann, Senator	Labour party, Representative of high flood risk area
11	Cllr. Paddy McCartn	Dublin City Council, Councillor	Fine Gael, Representative of high flood risk area
12	Cllr. Claire Byrne	Dublin City Council, Councillor	Green party, Representative of high flood risk area
13	Mr Mark Adamson	Office of Public Works (OPW)	Engineering System Management, Assistant Chief Engineer
14	Dr. Conor Murphy	National University of Ireland Maynooth	Resilience Academic Researcher, ICARUS
15	Mr Kevin Moran TD	Dáil Éireann, Teachta Dála	Independent, Minister of State for the Office of Public Works and Flood Relief
16	Mr John Murphy	Office of Public Works (OPW)	Engineering System Management, Assistant Chief Engineer
17	Mr Jamie Cudden	Smart Dublin	Smart City Programme Manager - Resilient Technologies
18	Mr Eoin Sherlock	Met Eireann	Chief Hydrometeorologist Flood Forecast Division
19	Mr Dick Gleeson	Dublin City Council Dept. of Planning	Former head of DCC planning - expert on urbanism and systems change

Table 3.2 Contacted interview candidates

Once the interviews had been completed, analysis of the data was carried out in a reflexive and iterative process involving both inductive and deductive inference. To ensure the validity of the research it was essential that an analytical method was used in order to make sense of the data and to allow for the refinement of the RMF detailed in Chapter 4. The interview recordings were written up in full before the initial review where key words and phrases were highlighted. These highlighted sections were re-listened to on the audio recording to ensure the tone and meaning were accurately understood. These sections were then joined together first by panel to identify common

understandings across the expert groups and then by theme. This process of analysis and interpretation had important output for theory construction and impact on the RMF approach. This led to refinements of the RMF and modification of the analysis during the case study. This interdependent process, as summarized by Figure 3.3 below, took place as the interviews were analysed.

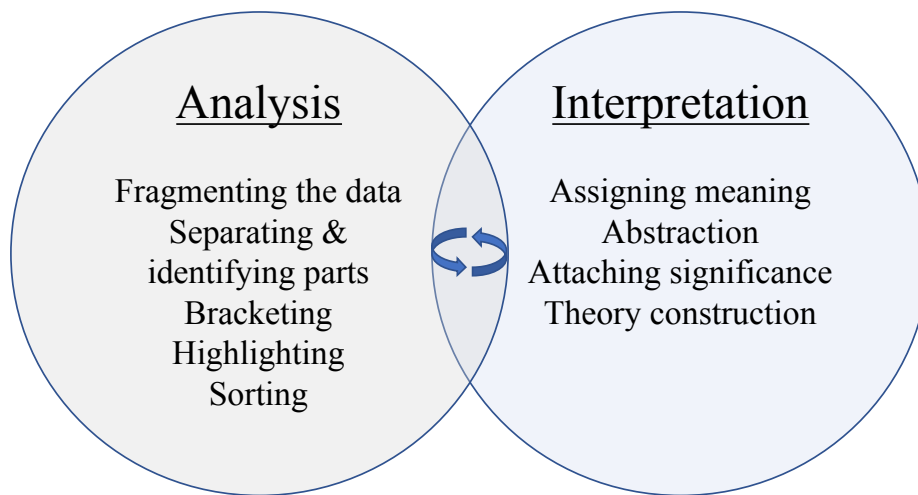


Figure 3.3 Recursive interplay between analysis and interpretation (based on Wolcott, 1994)

3.6.5 Data analysis methods

The case study may be viewed as an exploratory case study and so the data analysis for the research adapts similar methods as those used for case studies. For case study research, Yin (2009) suggests four general analytical strategies:

- (i) Relying on theoretical propositions - involves following the propositions underlying the case study;
- (ii) Developing a case description - is to develop a descriptive framework for organising the case study. This is more useful when lots of information have been collected without having first settled on an initial set of research questions or propositions. 'Studies started this way inevitably encounter challenges at their analytic phase' (Yin, 2009: 131);
- (iii) Use both qualitative and quantitative data; and
- (iv) Examining rival explanations - involves setting up a framework to define and test rival explanations. This generally works with all of the previous three

strategies if, for example, the initial propositions have included rival hypotheses; or if the contrasting perspectives of participants have produced rival descriptive frameworks.

Although aspects of each of these strategies are utilised in the case study, this research primarily uses the third strategy with analysis of both qualitative and quantitative data. The qualitative data from the interviews is used to validate the research outputs and initial framework development, while the analysis of the urban environment is quantitative in nature with the use of GIS and industry sensor tools. The study conditions are outlined in further detail through Chapter 4 in the STS development, and again in Chapter 5 in the case study itself. The data analysis approaches and the three tool types are outlined in the following paragraphs.

In Chapter 3 a KRNW procedure for gathering interview data was supplemented by the analysis of the empirical material during the research process. By ‘empirical material’ the interview reports containing the analysis of the minutes, fragmenting the data, separating and identifying key parts, bracketing, sorting and interpretation. Assigning meaning to the language, abstraction and attaching significance, theory construction using CMap Tools. Responses returned by the interviewees (13 expert interviewees). The method consists of three interdependent stages: preparing data, conducting data analysis, interpreting & representing data. There was significant overlap and interplay between the stages, rather than a strict linear sequence. In the following paragraphs, each of these three stages is outlined.

Computer assisted qualitative data analysis software ‘CAQDAS’ tools such as NVivo are commonly used to organise qualitative data systematically. Both Stake (1995) and Yin (2009) recognise the importance of organising data effectively. The data sets used in qualitative data analysis tend to be large and cumbersome, even though samples may be small. They require intensive examination, understanding and, therefore, organisation. Organisation can be achieved manually or with the assistance of software, there are several CAQDAS tools available.

CAQDAS use the coding method to structure, organise and sort through data. In qualitative research, coding means to attach a label or tag to a selected data segment,

usually by assigning a word or phrase that summarises a section of language-based data or visual data. Coding can help catalogue key concepts and themes while preserving the context in which these occur. However, CAQDAS do not ‘analyse’ data, this remains the task of the researcher, they simply aid data management and simplify the handling qualitative data sets (Burnard et al., 2008). Thorne and Kirkham (2004) state that none of the CAQDAS are capable of the intellectual and conceptualising processes required to transform data into meaningful findings.

This is an iterative and reflexive process of examining the responses and unlocking information by hand and mind rather than using software. The analysis was guided by resilience theory and the conceptual framework concerning STS (presented in Chapters 2 and 4 respectively). The aim was to develop a qualitative understanding of key characteristics of the STS and identify those that are crucial to resilience. The analytical process can be described as moving deeper and deeper into understanding the information (Creswell, 2009). This was achieved by reading and rereading the prepared empirical material, looking for key points, concepts, themes, patterns and relationships – a process assisted by the techniques concept mapping.

The process of qualitative data analysis involved in the expert interviews necessitated that the researcher remains open to a combination of deductive and inductive analysis. In summary, the aim was to make sense of the data collected by identifying important themes and meaningful patterns. From this point, through the feedback loop learning process the initial theoretical basis of the RMF was reconsidered and reconceptualised where necessary.

Through this research, the IHMC CmapTools v6 concept mapping software program is used for organising the information. The expert’s responses are categorised and organised according to the interview minutes and given answers. Convergence of the given answers aid in the initial exploration of the responses and the development of a general sense of the information. Initial emerging themes will be identified.

The data needed for the DRI development required a novel Geographic Information System (GIS) approach. GIS tools such as ARCGIS are commonly used to organise geographic spatial data with other data points so that they can be visualised and

understood in ways that would be otherwise impossible. During this research, QGIS v3.6, a geographic information mapping, system was selected to organise information, compare data sets to inform the DRIs and to visualise links between indicators. When researching which platform to use the fact that QGIS is an open source geospatial foundation project which is freely available, weighted heavily on the consideration when comparing it to ARCGIS which is a commercial product. Another factor in this consideration was that the researcher was familiar with the QGIS platform having previously worked on FP7 projects where the tool was used for indicator visualisation. The use of QGIS for the DRI development and visualisation is further detailed in Chapter 5.

In Chapter 4 the selection of industry-based solutions was necessary to improve the resilience adaptability of the water management system which led to the use of the Apollo sensor platform. The use of this platform for data gathering data and analysis was also adapted after thorough research of leading sensor types and the issues with different technology types as well as the input from industry partners through informal consultation meetings (as outlined in Chapter 5). The accuracy of the readings and data from this tool are important, but the use of new disruptive technology have important impacts on the management of STS. The Apollo was used to assist with understanding the STS being studies, e.g. system properties within their context and to uncover links between concepts and develop themes.

3.7 Summary

Chapter 3 describes the overall approach and methods for addressing the research problem and questions identified in Chapter 2.

This chapter chartered the researcher's philosophical stance and methodological perspective for this research. The methods for the development and testing of the RMF were explored as well as the validation strategy using expert opinion. Instead of maintaining a static position adopted at the beginning of the research process was allowed to develop as the research progressed through the multiples stages. The chapter began by examining the fundamental rationale for this research, which was the production of usable and effective knowledge for resilience of complex, STS. The

chapter then explained the research approach for addressing socio-technical relations and interactions. It located the study in a hybrid frame of reference for urban resilience research consisting of risk management, resilience theory and an STS approach.

Turning to the methodological aspects of this research, the chapter provided justification for the development of aspect of the RMF and their testing as part of a single case study involving a macro regional study of Dublin. It explained the rationale behind the mixed methods research strategy adopted for the study of urban resilience in Dublin. Finally, the chapter described how the RMF would be validated through the selection of an expert panel, the elicitation strategy for gathering their opinions and their analysis. This involved the knowledge resource nomination worksheet method of interviews.

CHAPTER 4 RESILIENCE MANAGEMENT FRAMEWORK

This chapter focuses on designing a strategy to measure and enhance the resilience of STS, it examines the theoretical basis and development for each stage of the Resilience Management Framework (RMF). The Disaster Resilience Indicators (DRI) analysis presented in Section 4.5 offers an approach to the quantification of a baseline resilience score. These scores can then be used to improve the resilience of the STS.

4.1 Introduction

The role of resilience science is to address the intrinsic complexity of the dynamic interactions between co-evolving systems within the urban environment across a range of scales. In this way, resilience theory provides a knowledge base for the design, implementation, and impact measurement of management decisions and interventions to promote the resilience of the local urban environment. Accordingly, this chapter investigates the application of the theoretical concepts of resilience outlined in Chapter 2 and their conceptualisation through the RMF.

This chapter describes how resilience can be applied to multi-level adaptive management through the creation of a single management framework. It answers the third research question (RQ3): Can STS be managed to reduce vulnerability to multiple hazards, increase capacity to tolerate and deal with change, and so achieve regional urban resilience?

The framework is built around a foundation of the DRIs, which are detailed in Section 4.5. The DRIs themselves offer an initial benchmarking tool, which can influence any further resilience management decision-making. The DRIs are the most influential and detailed of the 6 RMF stages. The development of each of these stages and the associated tools are outlined in further detail through this chapter.

The development of the RMF was an iterative process of incorporating different management approaches, methodologies, and standardised tools, which were developed from best practice risk management, informed by the literature review and with input from the experts; these included the European Risk Assessment Guideline and relevant supporting tools. The draft RMF was subject to testing on a case study involving the

Dublin City Council led Internet of Things (IoT) Flood Research Consortium and the Dublin Smart Docklands initiative, which were used to further refine the RMF.

The application of the RMF to the Dublin water management system aims to demonstrate how these methods can be applied in a live study and are appropriate to meeting the principles enumerated as a conclusion of the literature review in Chapter 2. The alignment of the outputs of the review by the expert panel through interviews in Chapter 5 and the results from the case study in Chapter 6 demonstrate the suitability of the RMF methodology for the purpose of appraising resilience.

The outputs from the extensive literature review, as outlined in Chapter 2, and the researcher's work on the H2020 Realising European Resilience for Critical Infrastructure (RESILENS) project and collaboration with Smart Dublin and Dublin City Council (DCC) informed the theoretical basis for the first draft of the RMF. This draft underwent peer review and further criticism after its presentation at the IRSPM international conference in Edinburgh in May 2018. The inputs of the peer review and the feedback from the commencement of the case study led to the second draft. The expert interviews detailed in Chapter 5 provided further feedback which informed the stages of the RMF development, which are outlined in Figure 4.1

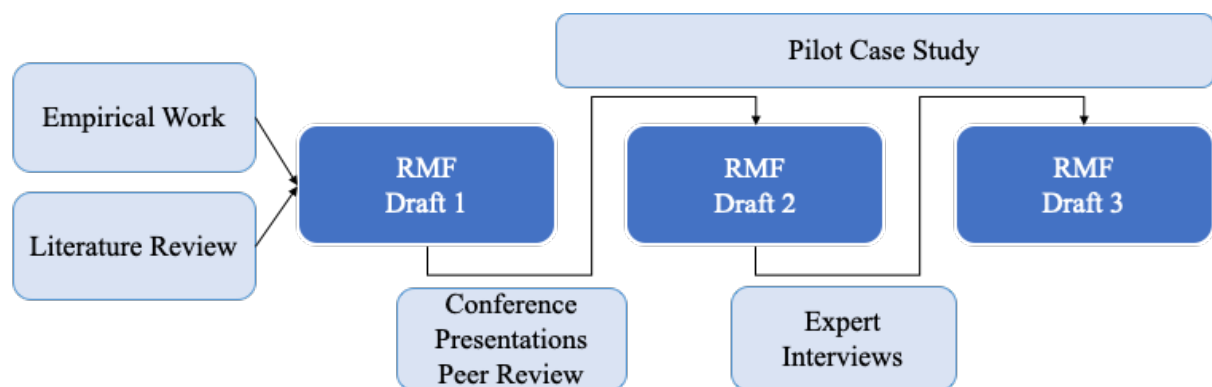


Figure 4.1 RMF Development Process

4.2 Resilience Management Framework Approach

This section discusses the use of resilience management and the range of strategies for managing resilience in STS. The issue of how to measure resilience has been addressed through management frameworks, indicators, and case studies through the scientific

literature (Hosseini, et al., 2016) see Section 2.6. These tools, however, are often conceptual in nature or at the stage of early proof of concept. This chapter will introduce the managerial steps used to move resilience from a conceptual understanding to a practical and operational management framework. This framework integrates the best practices across current resilience thinking, risk analysis and management approaches. As a result of this research, the RMF was developed, this framework aims to support the practical application of resilience to communities and the critical infrastructure (CI) systems that support them, together these are considered as an STS.

As detailed in Chapter 2, mitigation and adaptation have proven to be useful strategies to prepare communities for disaster events and to reduce vulnerability (Cutter et al., 2008). Based on the examples of the New Orleans flooding in 2005 and the Fukushima power plant tsunami in 2011, it is evident that the vulnerabilities of an STS are often only made fully clear after a disaster event has taken place (Chamlee-Wright and Store, 2009). Climate change has increased the likelihood of natural disasters on a larger scale than has been witnessed in the recent past. In order to reduce vulnerability, mitigation strategies can be put in place for certain disaster scenarios however true community resilience is needed to achieve an adequate post-disaster response. The characteristics of resilience which the RMF focuses on are:

1. Robustness; avoidance of direct and indirect economic losses,
2. Redundancy; untapped or excess economic capacity,
3. Resourcefulness; stabilising measures (e.g., capacity enhancement and demand modification, external assistance, optimising recovery strategies), and
4. Rapidity; optimising time to return to pre-event societal function levels

The primary components of the RMF are a set of resilience indicators, DRI, which will enable urban networks to have their level of resilience quantitatively indexed. These indicators will allow for the quantitative analysis of the resilience of the urban system across different spatial scales across Ireland, including the city, county, province and national scale. This information can then be iteratively used to direct users to aspects of their systems where resources could be concentrated in order to further improve their resilience levels. The RMF and associated tools are reviewed, tested and validated

through stakeholder engagement in the expert interviews outlined in Chapter 5, and the large scale case study of Dublin in Chapter 6. The RMF also consists of learning and educational material that provides further guidance and training on urban resilience for the stakeholders. Overall, this research aims to further advance the state-of-the-art of urban resilience management, and intends to increase and optimise the uptake of resilience measures by a range of stakeholders across academia, city management, and infrastructure service providers. The RMF shows how the research can move beyond the existing state of the art to facilitate the operationalizing of urban resilience.

This thesis adapts urban resilience theory and applies it to STS. The theory of complex adaptive STS and the concept of resilience are described in Section 2.5. This subsection briefly looks at how the design and application of the RMF to STS influences its design.



Figure 4.2 The Resilience Cycle

The resilience cycle, as outlined in Figure 4.2, which is an advancement of the earlier adaptive cycle (see Figure 2.1), acts as the theoretical foundation for the RMF. The sequence is designed to be circular and iterative rather than linear. It allows the analysis of single particular aspects (e.g. social, economic, technological, or physical aspects) of urban development. Findings from each iteration were used to modify the initial design and make it more resilient, thus closing the loop. These feedback loops are inherent to

the design of the model, which continues to be reviewed and enhanced as testing continues.

The design of the framework adapts four common themes identified in the urban resilience literature, the design is based on:

- (i) The resolution of organisational issues;
- (ii) The involvement of agents to understand and address their concerns;
- (iii) The framework should be iterative in nature with a clear process of diagnosing, planning, acting and evaluation, and;
- (iv) The framework should be applicable outside of the case study (Bruneau et al., 2003).

Resilience management is built on a multidisciplinary basis with inputs from risk management, complex engineering and even ecological systems. Characteristics that are cited across these research disciplines as contributing to the resilience of various systems and which the RMF should contribute towards are outlined here:

- (i) Fail-safe - the system's ability to absorb shocks or to slow the impacts to avoid complete system failure. This also refers to the interdependency between systems where the failure of one system should not impact on another through cascading impacts;
- (ii) Redundancy - this is the spare capacity to accommodate for contingency planning; and,
- (iii) Flexibility - the ability to convert assets and or to modify structures to introduce new ways of adapting system functions (Tyler and Moench, 2012).

These characteristics of resilient systems view STS as complex urban systems rather than the traditional view of linear technical prescriptions. These should be seen as guidelines for what the RMF will seek to achieve.

In working with practitioners and colleagues on resilience projects on a daily basis, it became apparent that a 'one size fits all' approach in terms of trying to research and develop resilience measure to address any disaster event type would be impossible. The research project outputs would be too general and have limited applicability to real world scenarios. With this in mind, the RMF is designed to improve the resilience of a

primary disaster event based on risk analysis protocols. The STS based resilience method is structured in six steps (Figure 4.3).

The six stages of the RMF are outlined here:

(S1) Building resilience awareness – concerned with educating agents about resilience through interviews, surveys, project work, team meetings, and brain storming sessions. (Section 4.3)

(S2) Selection of essential organisational components – built by the researcher as a tool for the European Union (EU) H2020 RESILENS project this tool identifies core assets within the STS. (Section 4.4)

(S3) Disaster Resilience Indicator (DRI) assessment – the DRIs are designed to give a baseline resilience benchmark of the STS, this resilience score can be monitored as improvement measures are taken. The resilience of different STS can be compared and contrasted. (Section 4.5)

(S4) Prioritisation of vulnerabilities – this stage uses the outputs of stages 2 and 3 to identify vulnerable assets. A secondary part of this stage is the plotting and visualisation of agent interactions to show interdependencies with other systems and stakeholders. (Section 4.6)

(S5) Increasing the adaptive capacity – Stage 5 is concerned with the adoption of measures including new technology to improve the resilience of the system based on the weaknesses identified by the DRI. (Section 4.7)

(S6) Recovery and reconstruction – the recovery phase identifies implementation and adaptation strategies to retrofit the STS with resilient materials so that functionality is improved after a disaster event. (Section 4.8)

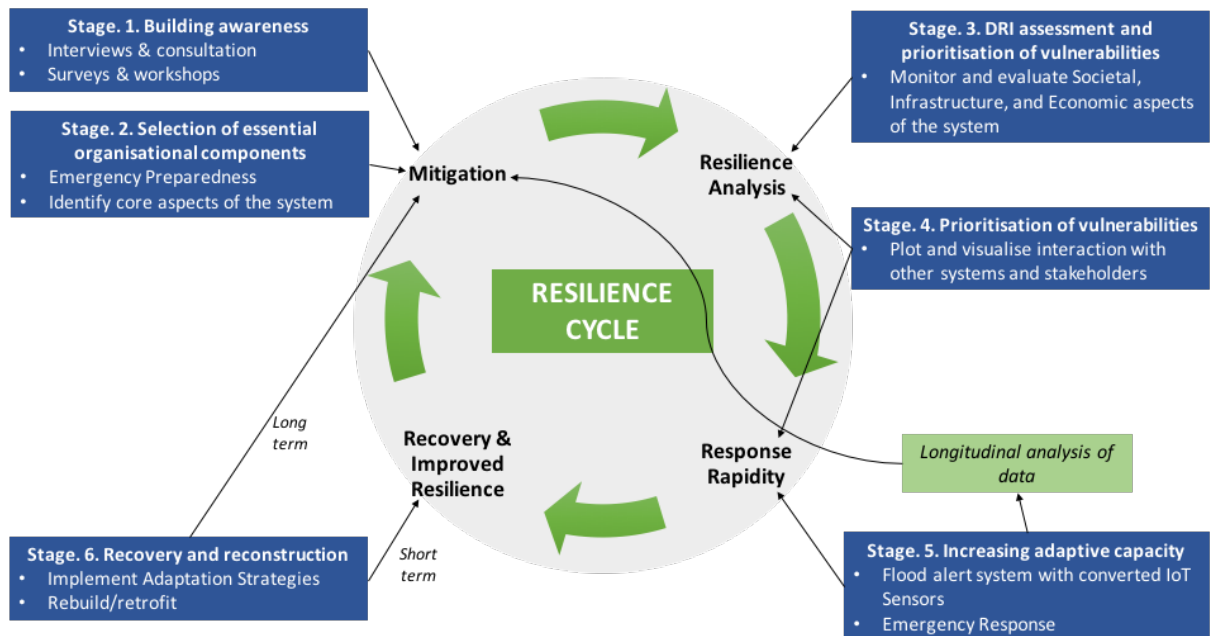


Figure 4.3 RMF fit with the resilience cycle

The RMF design process has been informed by the RESILENS project approach to framework development. It has been applied at several scales of intervention, at different levels of complexity, and from different discipline-specific standpoints. Following the literature review in Chapter 2, a number of resilience characteristics inherent to the development of the RMF and the RESILENS based methodology are summarised:

- The systemic nature of the urban area where the RMF will be applied requires the linking of spatial scales and is time-based. The case will adapt current best available data along with risk based projections for future trends. Therefore, any analysis will have to consider current options for development and their suitability to different future conditions. Moreover, the identification of the conditions for the future functioning of the option appraised inevitably requires evaluating risks at a regional or urban scale that have an impact at the development scale;
- The RMF method interprets the concept of resilience broadly and in relation to the urban environment as a whole, not in relationship to any specific expert's area. The RMF therefore transcends individual interpretations of resilience and focuses on the capability of the particular urban context being examined. However, because of its case based testing, it is capable of connecting 'detailed

resilience’ (i.e. the resilience of the examined system, i.e. the water management system) with the broader urban resilience of the entire STS;

- The RMF method emphasises the necessity to define finalities to resilience. It is an important step that helps answer RQ2: ‘How can the resilience of STS be determined?’. In particular, the method utilises indicators of urban resilience, thus linking the concept of urban resilience to the one of STS;
- The RMF method is used here as a mixed methods form of appraisal, in doing so, it does not restrict opportunities to select technologies or formulate design strategies;
- The RMF prompts users to be involved in the analysis process as opposed to ascertain scores through conformity to checklists.
- A case study offers a systemic representation of the urban environment, which is capable of capturing the physical (engineering), environmental, social, and economic dimensions of that context and, through their narratives, to connect them and elicit interplays.

The theoretical basis of each of the RMF stages is described in the following sections (4.3 to 4.8 inclusive). The core stages of resilience measurement, prioritisation and increasing adaptive capacity are continued through the expert review and to case testing. The Case Study in Chapter 5 and the Case Study in Chapter 6 detail the functionality and initial results obtained from the RMF. Figure 4.4 below outlines the breakdown of these stages and how they are dealt with in each of the review phases:

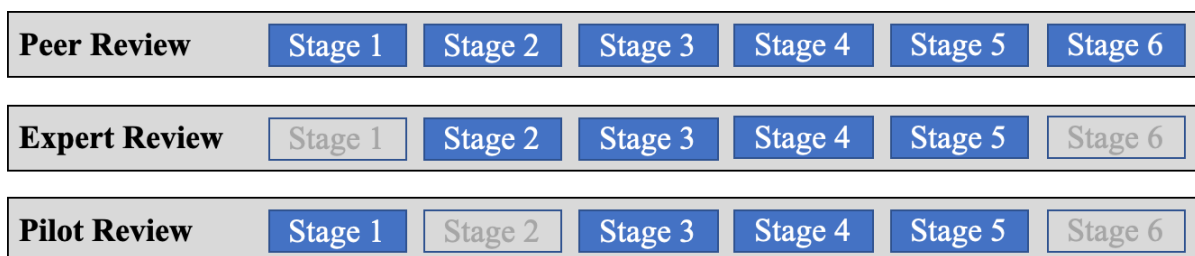


Figure 4.4 RMF stages and review phases

4.3 Building resilience awareness (S1)

Building a disaster resilient city goes beyond changing land use and physical facilities. The first stage of the RMF consists of building an understanding among the decision-

makers across each level of the STS and, where necessary, educating them on resilience issues. Fostering the adaptive capacity of actors is a central approach to both reducing vulnerability and enhancing resilience in STS (Engle, 2011). By consulting the key agents within the STS, the purpose and the circumstances and features of the system can be better understood and allow for the application of the resilience measures. Key agents may be identified in a similar process outlined in Chapter 5 for the selection of expert panellists using the KRNW.

A resilient city must be inclusive of the many local communities that need to collectively anticipate and respond to disasters. Based on a study of 11 earthquakes across nine countries, citizens in a risk-prone community share both risk exposure and mitigation responsibility, effective threat reduction and disaster response require collective action (Comfort, 1999). The study also demonstrated that advances in information processing and dissemination facilitate collective learning and self-organisation. By linking information technology to organisational learning, the collective within the STS will be better able to solve shared risk problems.

Although there may exist a hierarchy of management, there is no central control directing the specific behaviours of individual agents who rely on locally available information in relation to the physical system and other actors within and external to the system (Duit and Galaz, 2008). A set of tools is required to achieve an increased awareness of resilience issues among these key actors. These tools may consist of educating agents about resilience through semi-formal, open ended interviews, surveys, interviews, surveys, project work, team meetings, or brain storming sessions. Godschalk (2003) proposes a national campaign of research, education and training, and professional collaboration to increase knowledge and awareness of resilient city planning and design.

STS management practices with higher levels of deliberative public engagement, such as involvement, collaboration and empowerment can enhance both organisational and social learning for change (Petts, 2006). One such method involves emphasising the role of trust and its value for social capital and in building long-term compliance with environmental regulations. In order to ensure agents throughout the STS are provided with adequate information, managers must continue to foster awareness and advocacy

among local governments with strong emphasis given also to the national level authorities (Molin Valdes et al., 2013).

The resilience of the STS is not dependent solely on the management level agents, but the collective knowledge of the community. It is observed that more transparency and information about what citizens can do themselves to prepare for and react to disasters is required (Bharosa et al., 2010). More openness, to develop a dialogue between local authorities in the community, to talk about resilience-based projects, can be the link between citizens and the municipality. Communication through manageable experimentation with a wider stakeholder group will foster social learning and build the adaptive capacity of the STS facilitating adaptation under conditions of rapid, directional and often unexpected socio–technical changes.

In terms of the RMF, this step involves fostering and embedding both participative and deliberative forms of public engagement in planning and decision-making processes. The approach of negotiating and defining shared vision of resilience between agents is necessary, but is not necessarily explicit. This is a primary concern where adaptation of plans is actually implemented. Information paths, such as consultation during the early part of a project plan, websites, or simple solutions (for example, brochures) can have a huge benefit on the well-being of citizens. This step may also involve the creation of an information bank, which is easily accessible to citizens, to build awareness of emergency plans and of the ongoing work to build resilience in their communities.

The complexity and evolving nature of STS means that no one agent can form a complete understanding of the entire system (Kurtz and Snowden, 2003). Through their collaborative platform to facilitate engineering decision making, Wash et al. (2013) suggest that in order to aid collaborative understanding and decision making between the agents visualisation of the key issues and how they apply to different parts of the system are necessary to facilitate discussion and information sharing. An example of this may involve an overview of the potential risks visualised on a map such as Appendix F4. In order to establish any required solution for the particular STS being examined, a consultation process should be held with a range of key agents operating within the STS. These agents should consist of leaders across the STS and not necessarily just CI operators.

In order to select the appropriate agents the KRNW process involves the identification of the relevant disciplines: academics, practitioners, government officials etc., followed by the relevant organizations, and then the specific individual agents. This process is detailed in Chapter 5. Once the experts are selected, a consultation with them will give a better understanding of the entire system. Through the process of the consultation, at the very least, a more clear common understanding of resilience will be fostered. Further steps can be discussed and undertaken through the discussion with other agents.

4.4 Selection of Organisational Components (S2)

The asset selection tool, which enables CI operators to determine the core assets of STS, was designed with the aim of aiding the development of suitable resilience strategies. Indicators were developed to analyse the importance of the core assets based on their financial cost, criticality to operations, preparedness for disaster, susceptibility to an event, and the societal impact the loss of functionality would have. Conventional approaches for evaluation do not significantly contribute to the achievement of resilience in the urban environment. Recent research highlights the need to focus on a starting point of systems whose operations are essential for community functionality and well-being. CI are also considered to be important for the ability of the society to respond following disruptive events, since urban societal continuity is heavily dependent on the availability of the functions provided by these systems during and after disaster events. Improving the resilience of these CIs is therefore crucial for boosting the overall resilience of the considered communities. The conceptual asset selection tool was discussed with RESILENS partners at table-top discussion and included in the project as a relevant related tool.

Although previous research has focused on developing methods aimed to improve the resilience of certain CI systems, there has been a lack of studies into how these systems are identified. Furthermore, consideration is needed as to which assets in such CI systems can be considered as core assets. Once selected these core assets should be given priority with regards to implementing resilience enhancement practices.

This study puts forward a methodology to determine the core assets of CI systems, with the aim of aiding the development of suitable resilience strategies. The benefits of this approach are especially clear in relation to geographical regions and entities interested in identifying what physical or virtual assets can be rightly denoted as critical within their boundaries. Thus, these methods have an important application in urban resilience and emergency planning activities.

4.4.1 Core Assets

The ambiguity in the appropriation of the CI sectors (as well as the changing list of infrastructures) was, however, highlighted as a potential major issue which might generate debate among policymakers and relevant technical and business stakeholders. Ambiguity about what constitutes a CI and the critical assets contained in it could lead to an inefficient use of limited domestic resources. An unstable understanding of what constitutes a CI could in turn lead to inefficient security policies, as was highlighted by Moteff and Parformak (2004). This was exemplified in the US congress report by private sector representatives (Moteff and Parformak, 2004) stating that they needed clear and stable definitions of asset criticality so that they will know exactly what assets are important, what assets to protect, and how well to protect them. Otherwise, they risk the possibility of having too broad a list, which may result in protecting unnecessary facilities. A clear ‘criticality’ criterion was also deemed to be highly important for federal agencies who intend to implement and enforce potential future security regulations related to CI (Moteff and Parformak, 2004).

In the US, in an effort to establish and implement a more consistent standard for what constitutes a CI, the Department of Homeland Security (DHS) is required to develop a uniform methodology for identifying facilities, systems and functions with national level criticality (Moteff and Parformak, 2004). In advanced countries, a similar system for asset identification is likely to exist, it is acceptable that where these systems are in place that they should be adopted. However, if asset identification is not already present a new system must be put in place.

The Information Analysis and Infrastructure Protection Directorate (IAIP) office in the DHS charged with the development of this methodology and an accompanying core

asset catalogue in the U.S. has, however, faced problems advancing and implementing such methods and lists. This is in part caused by the US agency-by-agency approach, which is disjointed (Larkin et al., 2015). For example, among energy utilities, questions were raised as to why some assets not in use or not supporting significant loads were listed as critical by IAIP, and why the list developed by IAIP was inconsistent compared to core asset lists developed by state agencies (Moteff and Parformak, 2004). A clearer method that can be applied across different government levels, and is less subjected to political and sentimental factors, is required to objectively identify a unified CI list.

While an objective assessment of the designation of CIs and assets is crucial, the fluidity of the ‘criticality’ of individual infrastructures and assets should also be acknowledged and should be properly (and periodically) assessed as a function of time, risk and market changes.

If the emergency response units in a city with limited resources receive information that an undisclosed infrastructure in a defined sector will be attacked or faces a natural disaster, there is often a question over how they can decide which facilities to best concentrate their resources on. Individual CI sectors have historically implemented independent and often varying approaches for the identification of their own core assets. With the first step in risk management processes typically being the identification and valuation of the key assets of the organisation, so the core asset identification in designated CIs can be largely left up to the operators. Since such approaches can be assumed to constantly addressed by CIs, internal strategies to designate their assets criticality will be highlighted, but will not be concentrated on in this study.

With regards to CI asset designation in the EU, Directive 2008/114/EC constitutes a first step in a step-by-step procedure for the identification and designation of CI systems in EU member states, while outlining a common approach for the assessment of these infrastructures. The EU member states make use of the CI identification process and selection criteria to identify potential CI, taking into account possible casualties (i.e. potential number of fatalities), economic (i.e. in terms of significance of economic loss) and public (i.e. assessed in terms of impact of public confidence,

disruption of daily life and physical suffering) effects. The cross-cutting criteria thresholds will be based on the severity of the impact of the disruption of an infrastructure, with the precise thresholds applicable to the criteria determined on a case-by-case basis by the member states concerned by a particular CI. The scope of the directive was, however, initially limited to the energy and transport sectors, while indicating the information and communication technology (ICT) sector as a priority for future expansion.

Directive 2008/114/EC also directs that EU member states are to implement an operator security plan (OSP) or an equivalent measure (as set out in Annex II of the directive) for each designated ECI to facilitate the identification of core assets of the ECI as well as existing security solutions for protecting them. Concessions exist, however, for ECI entities that already have similar measures in place, with the primary and ultimate responsibility for the protection of the ECIs falling on the member states and the owners/operators of such infrastructures.

Despite the objectives set out in this directive and the timelines indicated in it, previous research has indicated that a significant number of EU member states are currently faced with a low level of maturity and lack a structured approach for the identification of core assets (Mattioli and Levy-Bencheton, 2014). This is mainly attributable to the complexity of the definition of the criticality criteria needed in order to identify the core assets. Additional challenges encountered in identifying CI assets and services highlighted in a study by Mattioli and Levy-Bencheton (2014) included: The non-presence of a detailed member state tailored critical services list and a lack of effective collaboration between public and private sector stakeholders. The study stipulated that core asset identification is fundamental starting point in the protection of CI systems and services.

Methods to aid the identification of CIs and their core assets are therefore a vital and logical first step in any process to secure and guarantee the protection of the services provided by the CIs. In Europe, several member states have established different initiatives regarding how this could be advanced, and are in the process of developing their own approaches. The advancement of such a method will be the main focus of this research. The framework method and indicators proposed are designed to aid the

relevant owners and operators of CI organisations who intend to map out which assets can be regarded as core assets with regards to their function, economic and societal significance. The framework could also be useful for relevant mandated agencies and regulatory authorities in member states responsible for regional and national CI protection. From the point of view of the CI owners, the objective of such a method is to support them in their identification of core assets, which need to be secure. In case of disruptions, they require resilient interconnections, which in turn will ensure the protection and overall resiliency of such assets.

4.4.2 Assessment Approaches for Critical Facilities Identification

To date two broad methodological approaches have been implemented for the identification of CI (Mattioli and Levy-Bencheton, 2014):

- A critical service (CS) dependent approach, and;
- A non-critical service dependent approach.

While these approaches were initially developed for use specifically for information network infrastructures and services, with some adaptation these methods can be applied for use in core asset identification in CI systems. The latter does not involve an analysis of the particular assets, but instead looks at the infrastructure networks. Such methodology is usually based on an evaluation of the impact that a disruption of service can have on functioning of the affected society, and is normally achieved via one of two paths: Operator-driven processes and State-driven processes, as indicated in Figure 4.5.

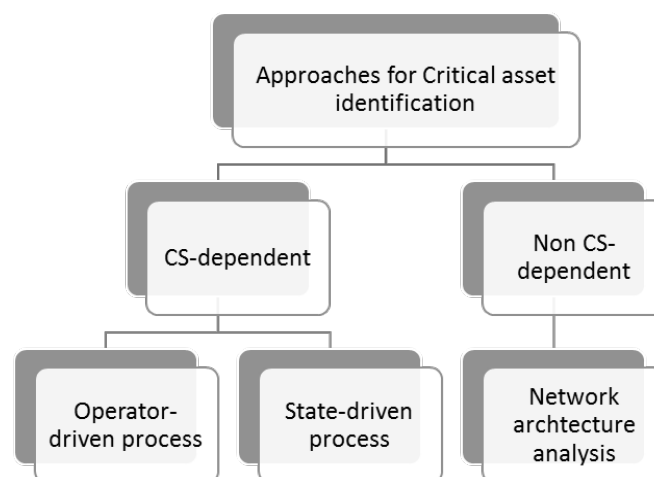


Figure 4.5. Methodological approaches for core asset identification (adapted from Mattioli & Levy-Bencheton, 2014)

The CS-dependent approach follows a 3 step procedure, where the critical sectors are initially identified using a government driven process (step 1), critical services identified (step 2) and the identification of core assets supporting the critical services (step 3). In the case of the state-driven approach, the entire process is governed by the governmental agencies with a mandate to identify and protect CI. After decision of critical sectors, they apply a method to identify the critical services and the CI operators involved in these services. The identification of specific assets may then be performed, usually in collaboration with the CI operators aimed at certifying effectiveness, aligned with societal needs. However, in the EU, the CI sector and asset identification is drawn from a combination of the state and operator approaches, with the operator-driven approaches playing a leading role for the core asset identification (i.e. the task of CI asset designation assigned to the CI operators). Here the concerned state determines a list of operators who are tasked with the identification of the services and assets within their own area of responsibility.



Figure 4.6. Steps for core asset identification. Overview of CS Dependent approach of core asset identification

While specific methodologies for the approaches outlined here exist, the support of these approaches for the designation of CI and core assets are not consistent and in many areas remain broadly lacking throughout the technical and academic literature.

4.4.3 Urban Environment

The overall intent of the asset indicators presented in this research is to better understand factors affecting the importance of individual assets for specific cases.

Together the selected indicators enable CI operators to monitor (or in some cases project) the role each asset plays in the overall resilience of the entire system. Drilling down to more local and context-specific applications of the proposed framework, one might identify indicators in the other three categories that capture the importance of a particular asset better than the derivatives of the current indicators.

In conjunction with the literature review, the indicators were developed from traditional risk measurement and resilience indicator frameworks. The indicators put forward have been subdivided into societal costs, economic costs and impact on the core function of the CI. These categories represent a distillation of the various theorised determinants of resilience across a wide range of studies. However, the categories (and the indicators within the categories) may need to be modified in specific cases. In some decision-making contexts, indicators or categories may not be necessary, and categories may be joined if indicators span two or more categories (e.g., when there is considerable overlap between indicators within a particular system).

From these three categories, the indicators that are most relevant to the particular CI will depend on the adaptation decision and which indicators prove most robust in relation to resilience enhancement (i.e., verification). Additionally, the framework, its three categories, and the indicators within these categories might change over time as other explanatory variables are gleaned from case studies, expert elicitation and evaluation. The iterative nature of the framework, along with the reliance on qualitative methods and stakeholder participation, highlight that the framework also includes a learning component, building an understanding of what determines a core asset. A challenge in implementing this framework is to identify categories and factors for which indicators and data can be collected at the variety of spatial scales which will be important to assessment and monitoring of changes in resilience as a result of adaptation measures. Thus, the selection of particular indicators will require considerable flexibility and continuous attention.

Within each of the three categories, individual indicators imply preferred outcomes for asset importance. Through the indicator development process, the ‘desired’ outcome for each indicator was made explicit, we were aware of the proliferation of undefined and,

indeed, unmeasurable ideals hinder progress of resilience research and is self-defeating (Donohue et al., 2016). Stakeholder participation and case study insights can provide the necessary flexibility and iteration to factor in changing understandings of what is (and is not) desirable for core assets and urban resilience.

4.4.4 Critical Asset Selection Process

This section details the development of a framework for the identification of core assets with the primary aim of its use in EU member states. While we will be using the EU region as a case study, the methods proposed will also be applicable in other regions outside the EU. In achieving this we build on the CS dependent approach in conjunction with the progress made in terms of CI sector designation methods, and use these as a foundation for the framework which will be proposed for application for the identification and listing of core assets and core supporting assets.

By applying urban resilience to STS by definition the entire system should be examined, however it is important to keep the primary assets that underpin that system in mind when identifying approaches to improve and protect certain areas within the system. By identifying critical assets within the CI resilience and prioritising them for protection, the resilience of the entire STS can benefit. The asset selection indicators put forward identify the natural market economic forces that will drive businesses (which include CI operators) and guarantee that they see the relevance of the RMF as a whole, an understanding of risks to specific threats and the value in guarding against them. The proposed indicators (as seen in Appendix A below) aim to analyse the importance of the core assets based on their financial cost, and the societal impact the loss of functionality would have. The indicators include important societal, political and even historical dimensions as well as in depth fiscal aspects. Through the application of this framework, the core assets may be identified and (in coordination with the DRIs) suitable resilience measures may be specifically designed on a case-by-case basis.

The indicators are put forward with the principal aim of providing support in the identification of the core assets of a designated CI. The assets covered in the development of this indicator set, which will be considered during the core asset designation process using the methods proposed in this document, do not include

current assets (i.e. cash, short term investments, prepaid expenses etc.); it is mainly applicable to physical facilities (i.e. plants, machinery or land). Once the core assets have been identified, the most valuable infrastructures can be protected using the available resources and time. This will be time dependent as the disaster event unfolds.

Due to the complexities of CI, a complete system-wide assessment requires planning and more importantly, a strategy that systematically increases the scope of the resilience assessment until it encompasses all infrastructure areas and the interdependent relationships therein. This strategy begins with the selection of the system's core assets. Using the step by step framework (Figure 4.7) together with the indicators put forward in this research, CI operators will have a clear picture of the importance of each individual asset and where the application of resilience measures will be most beneficial.

Our priority here is the identification of the relevant core assets in the CI system. For the method proposed in this document an assumption can be made that the various CI sectors to be analysed have been successfully identified by responsible government. In this instance, the identification of specific CI sectors is taken as given, as this has already been stipulated by the EU. Therefore, step 1 of the framework approach should be accomplished by previous and forthcoming government (EU, 2008).

Core asset identification may include people, facilities, services, processes, software programs, etc. The fluidity of these systems is key and defining the scope of the system may depend on the management body in charge, i.e. local government may have a broader view of the system when compared to a private provider which deals with one aspect of CI provision alone. Using the indicators put forward in this research, the identification of the 'impact of loss' for each asset can be estimated. This is a measure of the loss to the CI operator and the wider urban environment if the investigated asset is damaged or destroyed. The four main steps in this process are outlined in Figure 4.7 below.

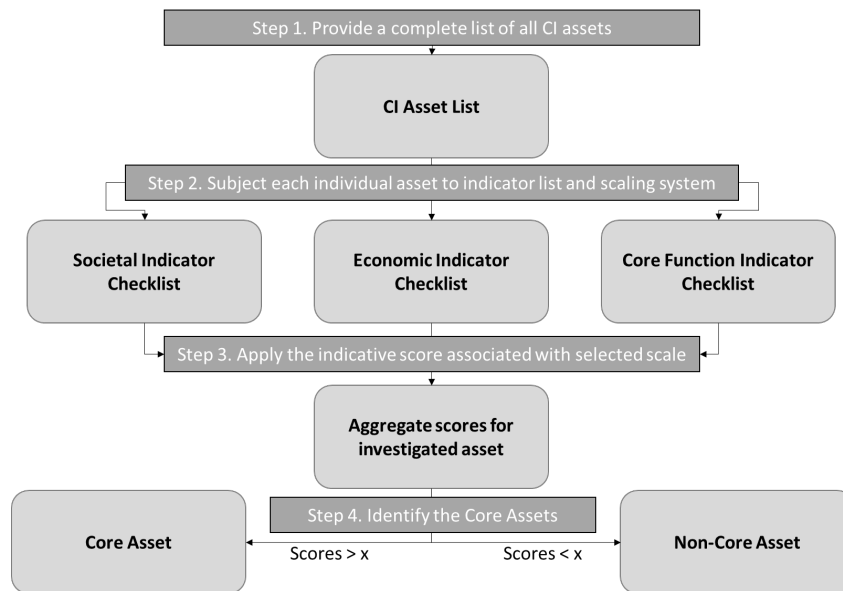


Figure 4.7. Overview of core asset identification framework

The first step of this framework involves the provision of a complete list of all assets within the CI system being examined. This information will be gathered to create an agreed working model of the system, so that changes and improvements can be visualised.

After all of the assets within the system have been identified, they are then scored under each of the separate indicator categories. The category division can be used to enable the end user to weight the score of the assets depending on the importance of each for the particular CI environment. As the asset is subject to each individual indicator on the list and scaling system, the operator will have a strong overview of the system regardless of the final weightings chosen.

Step three sees the application of the indicative score associated with the selected scale. This gives the operator a quantitative measure so as to easily compare the different assets within the system. Here the assets with the highest scores will be the most critical.

Using the scoring function provided in the preceding step, step four sees each of the assets divided into core and non-core lists providing a tangible points-based foundation which the CI owners and operator can ascertain which assets are considered as critical,

providing a basis for determining how resources can be best allocated to support the maintenance of such identified assets.

4.4.5 Application of the Framework

Through the application of various different weightings of the three indicator categories, contrasting target users could potentially implement the tool in very distinctive ways. The tool's primary function provides STS management at various levels with the means to select the core assets. This function focuses on the fiscal impact destruction a particular asset could have and the effect on the wider system. Through reinforcement of the selected core assets, operators will enhance the overall resilience of the CI system as a whole.

Additionally, the indicators together with the other RMF stages may be used by policy makers to complement their own decision-making processes. The effects of any planning decision at regional level could have a massive impact on a particular asset with knock-on effects for the entire CI. Through the application of these indicators, policy makers will be equipped to identify how important particular CI assets are to the local population. As policy makers will have extensive knowledge of the likely implications of their decision making the identification of core assets will be of great benefit.

The core asset identification indicator list put forward in this research will aid in the accurate provision of resources in the event of a disaster. This list will have particular relevance to government institutions especially with regards to military and response planning. These indicators will also aid STS management themselves through: Public-Private partnership functions. This is based on inviting the mostly privately run aspects of the STS to share information, i.e. the mutual benefits to government and businesses through the different government regulatory agencies, since these are the parts of government the private aspects of an STS care most about.

4.5 Disaster Resilience Indicator (DRI) assessment (S3)

This section describes the indicator development process as a tool for resilience measurement of STS. The DRIs are designed to give a baseline resilience benchmark

that can be monitored as improvement measures are taken. The DRIs are inclusive of the social, economic, and technical elements of the target system and aim to improve STS resilience strategies for the identified risk event: the DRIs are hazard specific which means that they are designed to address a particular threat but this threat. More than 50 variables were originally collected from the literature review which were then sorted and highly correlated variables were removed. 24 generic resilience indicators have been identified, these have been subdivided into the specific, but intrinsically related categories of community, economic, and infrastructure resilience.

Through a combined approach of literature review and action research, a framework and a set of indicators that aim to measure base level conditions of community resilience to disaster events, are conceptualised. These DRIs are devised to deliver a clear understanding of the initial conditions present in the community, how they relate to the CI, and to identify any improvement or decrease in resilience over time. As set out in Section 2.4, community resilience is critical in terms of addressing the resilience of the STS as a whole. In addition to social and economic metrics, the DRIs analyse the community's CI systems and its capabilities. The DRIs will thus be able to measure the effectiveness of new policies, investment in infrastructure, communication strategies, and interventions designed to improve community disaster resilience. Policy makers and CI managers may employ these empirically based DRIs to benchmark pre-existing conditions to improve their community resilience.

4.5.1 Composite Indicators for Disaster Resilience

In their seminal paper Cutter et al. (2008) highlighted that relevance or validity of the resilience indicators depended on their ability, not only to benchmark the baseline conditions effecting community resilience, but importantly the impact a disaster event has on the community's ability to respond. Indicators are necessary tools to set benchmark levels of community resilience and they are also necessary for the identification of those elements that contribute to the community's vulnerabilities that lengthen (or shorten?) the post-disaster recovery process. These indicators can then be used to provide national and local governments with the metrics to measure improvements in community resilience, set priorities areas for investment and location of emergency services, and reduce ambiguity in the decision-making process. Once

benchmarking is introduced policy makers are able to use this information to contrast the resilience levels of comparative communities and compare their respective performances which enhances decision making.

The information provided by the DRIs may be used by policy makers as a performance measurement tool. The information can also be used not only to show the communities resilience but how this is impacted by new policies which can then be communicated to the public (Saisana and Cartwright, 2007). Although the case study will focus on the threat of flooding only, composite indicators are widely used to identify how any natural or technological hazard will impact on society, an example of this is The Social Vulnerability Index put forward by Cutter et al. (2003). Through an extensive literature review of the resilience indicators, the leading indices of societal resilience were selected include those in Table 4.2 and further details on the metrics and references for each of the DRI can be found in Appendix B. While there are a wide range of societal indices focusing on all aspects of social vulnerability, very few mention infrastructure or CI resilience to any great extent.

	No.	Indicator	Metric
Social Resilience	1	Educational Equity	Ratio of the pct. Population with 3rd level education attainment
	2	Health	Percentage population with good health
	3	Population Coverage	Population in the area
	4	Local affluence and deprivation	Poball Haase Pratske Score
	5	Municipal Services	Proximity to fire stations
	6	Dependency	Population over 65 and under 15
	7	Voter participation	Voter participation
	8	Cultural diversity	International population
Economic Resilience	9	Owner occupied housing	Housing lived in by their owners
	10	Female Unemployment rate	Percent working age population (M/F)
	11	Male Unemployment rate	Percent working age population (M/F)
	12	Land value	Monetary value of system development
	13	Interdependencies with other urban systems	Linkages with other assets in terms of the inflows and outflows, showing the importance for the CI network
	14	Housing Stock	Housing available in the community
	15	Derelict Buildings	Derelict buildings in the community
	16	Vacant Buildings	Vacant buildings in the community
Critical Infrastructure Resilience	17	Low risk areas	Local risk of primary disaster in the area
	18	Medium Risk areas	Local risk of primary disaster in the area
	19	High Risk areas	Local risk of primary disaster in the area
	20	Redundancy	Availability of a redundant CI
	21	Retained spare capacity	The average operating level of assets in the area as a percentage of the maximum possible
	22	Mitigation Plan	Availability of local flood mitigation plan Y/N
	23	Previous disaster experience	History of disaster events in the CI domain
	24	Critical assets	Critical assets of the infrastructure being investigated

Table 4.2 DRI Shortlist

4.5.2 Data and methods for measuring disaster resilience

The literature review revealed a wide variety of models for index construction which had particular strengths and weaknesses depending on the scenario in question. The Disaster Resilience of Place (DROP) model which we have adopted presents a theoretically grounded, vulnerability and resilience relationship which can be tested. The DRIs are applied to the case study and reviewed by the expert panel by way of verifying their practicality and applicability to modern STS.

Stemming from the early ecological definitions, as highlighted in Section 2.2, resilience has been primarily used within natural habitats and ecosystems, however the importance of social and organisational systems' resilience is gaining recognition

(Magis, 2010). The core function of the DRIs is to establish the baseline resilience conditions across various communities. Communities and CIs are interdependent across different levels and scales, these interdependencies impact on the antecedent resilience conditions. The DROP framework achieves this by primarily focusing on these antecedent resilience conditions. Through this research, this framework is enhanced to incorporate the potential disaster elements by incorporating indicators across economic, societal and infrastructural schema.

The data sources for these indicators may be found from government bodies and publicly available sources however the critical infrastructure resilience (physical) indicators in particular may rely on input from CI operators.

4.5.3 Variable selection

Having selected the theoretical framework (DROP), the next step in the development of the DRIs is variable selection. These variables are representative of the community and are relevant to its resilience. The indicator literature is clear in outlining the criteria to ensure only quality indicators are selected. There is, however, no single set of indicators or framework that emphasises the importance of returning functionality to the CI network post disaster while also, essentially, analysing the impact of the disruption on the wider community and how this can be improved. Elements of other indexes may be adopted for the purpose of establishing this CI-centred community resilience. Due to the multifaceted nature of resilience, indexes have been developed across a wide range of theoretical backgrounds including; ecological, social, economic, community, and governance elements (Bruneau et al., 2003; Cutter et al., 2008; Gunderson, 2000; Norris et al., 2008). Based on these indexes, our own indicators are comprised of subcomponents from a host of theoretical backgrounds. These subcomponents are defined and described later in this Chapter.

Cutter et al. (2008) explain that there is difficulty in establishing the resilience of a community in absolute terms, therefore a comparative approach is employed where various indicators are employed as resilience proxies. Our variable selection was dependent on clear justification based within the relevant resilience literature and the availability of data from readily available government sources, such as the census 2015,

but also private data, which may only be available to the management of the relevant CI.

A final step of standardising the DRIs involved replacing any raw values with comparable scales i.e. phrasing the indicator description in such a way to allow the use of percentages or applying scoring bracket out of one hundred where percentages are not possible. This standardisation will prevent any issue with different measurement scales (King and Macgregor, 2000). An internal test was carried out to ensure consistency across the three indicator types - social, economic, and infrastructure; this allowed decisions to be made in terms of the indicator's relevance and applicability for community and CI disaster resilience. Over 50 variables were originally included, however, there was some overlapping and only unique indicators which fitted into the three types were included on the final index, this is consistent with the level of internal continuity which is accepted across the literature (Nardo et al. 2008). Twenty-four variables are employed in the final index (Appendix B).

The variables may be normalised using a min-max rescaling scheme. Here, each variable outcome has been given a score between 0 and 100. All other values can be scaled in between the minimum and maximum values. For some variables in which high values corresponded to low levels of resilience, our rescaling process also involves giving negative impact scores to their contribution to the overall resilience index before the rescaling process could take place. This is negative or positive impact is based on the literature review and expert input. The impact type is also detailed in Appendix B.

4.5.4 Components of disaster resilience

Our first subcomponent, societal resilience, captures the differential social capacity within, and to a lesser degree between, communities. Communities with higher levels of educational and health equality, and those with fewer elderly and disabled residents, exhibit greater resilience than places without these characteristics (Norris et al. 2008). Special allowances may be required to support those citizens who cannot support themselves and so these indicators are valuable to monitor changes in support over time. Clear communication plans, strong organisational linkages, and protective social systems greatly enhance the resilience of a community (Norris et al. 2008).

Economic resilience, the second subcomponent measures the economic vitality of communities including, employment, the financial cost of a disaster to the community, and the value of the infrastructure present. Variables within the economic component include a proxy for diversification (as communities largely reliant on a single sector will be less resilient to recovery), and the number of people in the community with long term employment will also greatly affect its resilience. Throughout history, dependency on a single key industry or resource, including the recent housing-led recession in Ireland from 2008, may lead communities to be particularly vulnerable with a spiralling boom and bust cycle. Adger (2000) outlines the threats an extreme weather event may have on any one economic sector.

CI resilience has a pronounced effect on the ability of the community to react and recover from disaster. However, as highlighted by the literature on STS, the resilience of the CI is directly related to the ability of the community to lead recovery and implement mitigation strategies. National government and local councils across Ireland are beginning to implement long term resilience planning and mitigation strategies as their benefit becomes clearer, reducing loss and hastening the recovery time. No two areas are alike in their capacities to sustain and recover from future disasters (Burby et al. 2000). Therefore, measuring resilience of STSs necessitates analysing the characteristics of individual communities and the CI as one.

4.5.5 Data aggregation and weighting

The weighting and aggregation of indicators are critically important steps in any resilience assessment. Weights of DRIs reflect the relative importance of different dimensions in their contributions to the resilience performance of an STS, while aggregation essentially reflects the substitutability of the different dimensions. The weighting method chosen for the DRI formulation has an impact on whether dimensions can compensate for one another or be substituted (Gan et al., 2017). However, the process of indicator integration is an inherently subjective procedure (Morse et al., 2001), and selecting appropriate weighting and aggregation methods is challenging (Wilson and Wu, 2017). Equal indicator weighting means that each indicator is given the same weight in terms of the overall resilience score. An expert

opinion-based weighting relies on inputs from the participating experts, whose judgments ultimately determine the weights to be assigned to each individual DRI. Thus, weights determined by expert opinion reflect the value judgments of the participants regarding different aspects of the research area (e.g., relative importance, relative urgency, or substitution rates) (Gan et al., 2017).

With regards to the weighting the DRIs, an equal weighting has been selected in the first instance, but the option of an alternative weighting may be selected, where necessary, by expert users to adapt to the specific context in which the RMF will be deployed. There are two reasons for the decision to choose an equally weighted index at both the sub-index and composite indicator level. First, this simple method of aggregation is transparent and easy to understand, a criterion we deemed important for potential users. Second, we find contrary theoretical and practical justifications for the differential allocation of importance across indicators (particularly between the expert interview panels with members exaggerating the importance of their own area and diminishing others). While methods exist for determining weights that are subjective or data reliant, such weighting schemes do not always reflect the priorities of decision makers (Esty et al. 2005).

A system of default weightings is applied to the DRIs in order to ensure that each of the areas of community, economic and physical resilience are considered equally and fairly in the decision-making process. The operationalization of the indicators in subsequent development work requires that default weightings be applied in advance of the final iteration. Assigning a default weighting is congruent with the majority of composite indices, as stated in the 2008 OECD report. It is recommended that, in order to enhance the utility of the decision-making, expert end users be allowed to establish the weight of each indicator in order to adapt to the context in which the tool will be deployed. In the long-term, testing will require a comparative basis between STS, which is prohibited with many different weightings.

Functionality of the DRI model is the main priority, this functionality is dependent on the indicators being transparent, user-friendly, accurate, fair, communicative and adjustable to local contexts. This flexibility is undoubtedly a great advantage; however, there is a balance between flexibility and comparativeness. Should the weightings of the

DRI be adjusted to specific needs of particular stakeholders, their direct comparability is reduced. Certainly, these characteristics necessitate trade-offs inherent in developing good theory (Weick, 1979). For an accurate and fair comparison, the weightings in this case would need to be maintained at the same level when measuring the resilience of both STS.

4.6 Prioritisation of vulnerabilities (S4)

This section discusses the steps involved in the identification, prioritisation and management of vulnerabilities and their impact on overall STS resilience. Stage 4 of the RMF involves inputs from the Selection of Organisational Components in Stage 2 and the outputs of the DRI assessment in Stage 3. The following discussion suggests how specific vulnerabilities may be prioritised.

Key vulnerabilities are those components of an organisational system that have the potential to cause the greatest negative impact, and may be catastrophic to the functionality of communities and CI within the STS (Smit and Wandel, 2006). The prioritisation of certain vulnerabilities can reduce exposure and sensitivity to disturbances adversely affecting the STS. Current and projected disturbances, in addition to the vulnerable areas affecting the STS, were identified by low scoring indices in stage 4 (Section 4.5).

The results of the DRI will inform decision-makers of the general areas of weakness within the STS, however, further examination and local knowledge is also required to prioritise specific vulnerabilities. An important point in terms of the structure of the RMF is the nature of the case-based analysis, which requires consideration of the characteristics of the STS and how they impact the option examined (e.g. for the water management system).

In the event that critical assets are present in equally vulnerable areas, a simple cost benefit analysis of the two assets in consultation with the key decision makers will decide which asset should be prioritised.

Typically, problems around vulnerability selection arise when different decision-makers in an organisation have different visions of the structure of the asset selection and the mitigation processes (Tolbert and Hall, 2015). The aims of these processes need to be clear to all stakeholders involved, and in particular those involved in the decision making process. The final list of vulnerabilities may involve include an in depth and detailed collection of specific tasks and actions for every conceivable event or a simple list of contact details for key stakeholders.

In the event of a disaster, these complex STS display characteristics of non-linear behaviour including cascading system collapses (Amin et al., 2000). Therefore it is critical that the key priorities for protection are selected and addressed far in advance of a disaster event. In addition to the vulnerabilities themselves the key actors within the system and the personnel they rely on through different levels of the STS must be identified. The Computer Assisted Qualitative Data Analysis Software (CAQDAS) tool described in Chapter 3 can be used to identify key personal and their relationships from a consultation process. Based on the outputs of the expert interviews in Chapter 5, the agent interactions with other systems and stakeholders detail relationships within the case case are plotted and visualised, see Appendix B.

4.7 Increasing the adaptive capacity (S5)

Based on the results of the vulnerability assessment in Stage 4, possible measures to enhance the resilience level are identified, prioritised, planned and implemented. The decisions on which measures to adopt, including new technologies, to improve the resilience of the system, are based on the weaknesses identified by the DRIs. The selection of measures is dependent on a range of risk factors, including the domain, the threat type and its expected impact, and the value of the system asset. Physical and technical protective measures may be planned and implemented, while measures needed to cover organisational and societal aspects should also be considered (Birkmann, 2006). In order to prepare the organisation to be capable of acting effectively in case of a disaster event, a change in culture may be required within an organisation. Inherent in this is the identification of the intended purpose of the required resilience solution. The solution must be fit for the stated vulnerability, and have the potential to address the vulnerability. Before the selection of adaptive improvement

measures may commence, first the precise purpose, the circumstances, and the features that require resilience must be established. Consideration should be given to how effective any proposed solution will be and to imagine the impacts the solution may have on the wider STS.

The identification of the tools to improve the adaptive capacity requires focusing on the contextual circumstances of the STS being studied. Managing the dynamic interplay between feedbacks that sustain fundamental system properties (including technical and social capital) of the STS and the disturbances that enable vital adaptations and create opportunities for reorganization and renewal (involving experimentation and innovation) leading to development along a desirable trajectory. As an alternative to the traditional adaptability approach of reacting to observed changes, Berkes (2007) suggests that enhancing adaptability involves proactive policies, strategies, and management practices to prepare, cope with and shape change. Examples of strategies to enhance adaptability for resilience in STS at macro-regional, national, regional and local levels include:

- **Risk prevention**, prevention measures aim to decrease the exposure of citizens and property via methods that prohibit or discourage developments in areas that are at risk. The main focus of the approach is on “keeping people away from harm” by only building outside risk prone areas (Godschalk, 2003).
- **Improving defence measures** aim to decrease the probability of disaster areas through infrastructural defence works or structural measures, which consist of options that increase the capacity of existing works to mitigate disaster events. Nature-based solutions (NBS) which refer to the sustainable management and use of nature for tackling socio-environmental challenges should also be considered as a beneficial option at this stage (Lennon et al., 2014).
- **Risk mitigation** focuses on decreasing the consequences of floods through measures inside the vulnerable area. Consequences can be moderated by smart design of the disaster prone area. Measures include smart spatial ordering inside urban areas, water retention within the protected area or retrofit and disaster-proof buildings. Disaster risk mitigation thus includes all measures to future-proof the built environment as well as measures to slow the onset of the disaster event (Godschalk, 2003).

- **Forecasting and warning systems** provide decision makers with additional data to make more informed decisions. Disaster impacts can also be alleviated by preparing for extreme weather measures include developing improved forecasting technology and warning systems as well as preparing disaster management and evacuation plans. Data gathering must be methodical, and rigorous to ensure that decisions are made on accurate information (Baklanov et al., 2018; Fleischhauer, 2008)

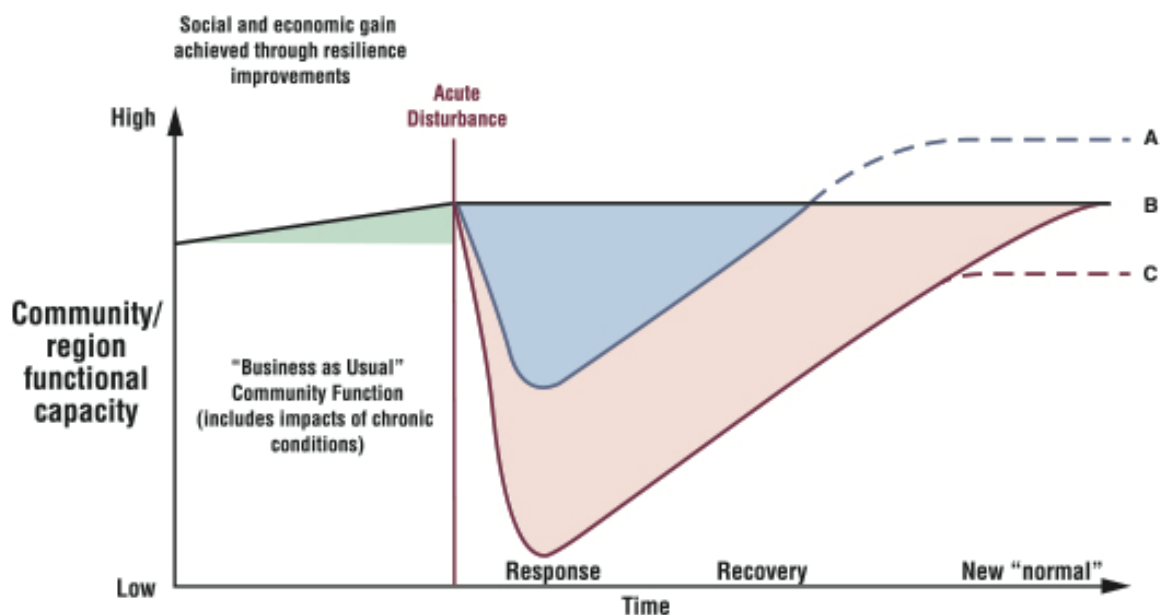
In addition to technical tools such as sensors and predictive computing programmes the adaptivity of the STS may also be improved by changes in existing multilevel institutional frameworks and governance systems to deal with accelerating environmental, social and technological changes. Governmental regulation and policy in particular are regularly ‘top down’ and urgently need to give agents at all levels of the STS more independence and thereby become more flexible (Chandler, 2014). As actors work to increase their individual fitness in relation to their own objectives, the STS is exposed to instability and a changing equilibrium. These kinds of complex dynamics inherent in STS, including vulnerability due to interdependencies between systems, must be accounted for. This can be achieved through improved communication between agents at different levels and across institutions within the STS.

The governance of STS requires decision making which goes beyond the scope of any individual actor (Smith et al., 2005). Fundamental changes to organisations of this nature will be required in order to move towards a more flexible problem solving and responsive system. In some cases cultures may require change if adaptive capacity is to improve, leadership is a key prerequisite in dealing with these changes in culture and how to incorporate learning and adaption approaches must be considered at this stage. Adaptive governance measures should be introduced to ensure sufficient adaptive capacity within the STS to address disaster impact.

Once the adaptive measures have been implemented, the core RMF process should return to the third stage to review the impact and effectiveness of the implemented measure. The realisation of adaptive technology tools from selection, to development and application is detailed in Chapter 6.

4.8 Recovery and reconstruction (S6)

Reconstruction has the aim of learning from the impact and feedback of the disaster event and improving resilience for the next iteration of the process (Haigh and Amaratuaga, 2010). A successful recovery will be efficient, timely and should improve the overall resilience STS from its pre disaster equilibrium. This can be achieved by retrofitting new adaptive complex management structures; facilitating the capabilities of the system to respond to and recover from future disaster events. In their 2010 paper Chang et al. put forward steps for resilient post disaster reconstruction; these steps are adapted and reconfigured for STS analysis. This section outlines the primary areas that STS can benefit from resilience recovery and reconstruction of STS post disaster.



4.8 Resilience Loss Recovery Curve (Dabson et al., 2012)

Beyond restoring functionality to the CI within the STS, the focus of recovery should be to help local communities to thrive rather than just cope with disaster (Norris et al., 2008). The complexity of STS necessitate that post disaster recovery requires solutions that go beyond standard procurement and construction (Kennedy et al., 2008). Resource planning in preparation for a disaster is not limited to the assessment and arrangement of supplies to rebuild, as often these supplies can be lost or used elsewhere or even stolen depending on the disaster event. Therefore beyond sourcing construction supplies, recovery includes the pre-determined plans to work with a range of

stakeholders in the construction industry and governmental agencies at each level of the STS, to activate desirable resourcing strategies and procedures (Chang et al., 2010).

The three main areas where resource relationship planning is required are transportation, funding, and legislation, each of these are explored in further detail here:

In the immediate aftermath of a disaster the delivery of relief resources to affected populations is the primary function of this emphasis for recovery measures should be on making transport networks clear so that lifeline networks can begin operating. In order to progress reconstruction of the STS the transportation network including road, rail, sea and air supply lines must be redeveloped. Once the immediate threat to life has been resolved the implementation of a reconstruction strategy can begin. This strategy should be implemented in a cost effective, economically and socially compatible manner to ensure improved quality, access and service delivery. However, the majority of the initial repair work is temporary and the access routes will remain prone to frequent disruptions induced by aftershocks in the wake of the initial disaster event. Rather than aiming to restore functionality to pre disaster levels the rebuilding of transport infrastructure connecting the STS should aim to upgrade specifications and thus reduce the vulnerability of restored accesses to a wide variety of future hazards (Brix, 2010). Pre event arrangements can be arranged with large-scale contractors (small scale contractors are more susceptible to the impacts of a disaster and so cannot be relied upon to respond) and competent resourcing professionals in resource acquisition within a disaster context should be managed to ensure they are facilitated to mobilise and begin reconstruction as quickly as possible (Chang et al., 2011).

Further to Stage 5, the increasing the adaptive capacity of the STS will allow for the timely recovery and return to operational functionality of the CI therein. The agent's goal is to implement adaptation strategies to restore the system's core services, preferably enhancing them above the pre-impact level, and to minimise any break in service where possible.

4.9 Summary

The security of STS underpins the resilience of the surrounding urban environment. The wide-reaching extent of these systems combined with limited funding means that

resilience measures must be focused and applied where the benefit of such actions can be maximised. The RMF is developed in six stages put forward as a robust step by step process to aid decision makers to improve the resilience of STS. The RMF is a management tool initially developed based on the literature review outlined in Chapter 2 and work carried out by the researcher on H2020 research project. This theoretical foundation was further refined by the peer review process at academic conference. The RMF is designed to be flexible and can be applied to a range of STS typed and is not disaster specific.

The first stage in developing a resilient urban environment is the consultation with decisions makers and stakeholders to ensure a shared understanding and awareness of resilience issues. This is followed by the selection of the core assets within the STS that are a priority for resilience protection. Through this research, a methodology to determine the core assets of CI systems is put forward, with the aim of aiding the development of suitable resilience strategies and maintaining their functionality. The goal of this study is to provide an approach that could be implemented for the identification of core assets to maximize the utility of often limited available resources. The third stage develops the DRI assessment with a definitive list of 24 indicators across economic, social and physical domains to benchmark the resilience of the STS. The main tools put forward in stages 2 and 3 are supported by suggestions for policy and management strategy development for the prioritisation of vulnerabilities, increasing the adaptive capabilities of the system and ensuring successful reconstruction in a post disaster environment.

The benefits of the RMF approach are especially clear in relation to geographical regions and entities interested in identifying what physical or virtual assets can be rightly denoted as critical within their boundaries, to develop a broader understanding of resilience through the DRIS and to uncover the necessary policies which should be developed. Thus, these methods have an important application in urban resilience and emergency planning activities.

In the following Chapters the RMF is reviewed by expert panels in Chapter 5 and the practicality and feasibility of the RMF is tested through the case study in Chapter 6.

CHAPTER 5 CASE STUDY OF DUBLIN

The case testing of the primary Resilience Management Framework (RMF) and the selection of appropriate associated tools are outlined in further detail through this Chapter. The RMF is partially tested through a feasibility case study where it was applied to the water management system in Dublin, Ireland. The steps taken to address each stage of the RMF and the challenges of realizing the theoretical framework are also discussed. While the design of the RMF and the development of the Disaster Resilience Indicators (DRI) are detailed in the Chapter 4, the specific tool selection for resilience enhancement is case dependent. Based on the output of the asset selection phase and the DRI analyses, in addition to input from the expert panel, Internet of Things (IoT) sensors were selected as the appropriate tool to enhance the adaptive capacity of the STS. The development, deployment and testing of these sensors is highlighted in Section 5.7.

5.1 Introduction

From local level flooding caused by a simple blocked gully, to an abnormal high tide impacting thousands of homes across the city, flooding has always been a major concern for Dublin. On February 1st 2002, although there was no heavy rain, an extreme flood event hit Dublin. Despite the relatively calm weather a centre of low pressure, 937millibars, located over Northern Ireland and southerly winds contributed to an unprecedented high tide. The predicted tide was 1.93m, while the actual tide was 2.95m. This was significantly higher than flood defences were designed to manage. Over 1,000 homes were flooded in East Wall, North Strand, Ringsend, Sandymount, Clontarf, Sutton and parts of Fingal. The receding tide collapsed 45m of the Dodder river wall leading to a further flooding of Stella Gardens housing estate, which primarily consisted of one-storey houses. The following day the tide returned to its normal pattern, however a major shock for the homeowners when they returned was the damage caused by the floodwater which took six months to return to pre-flood levels. The combined water management system, which manages water drainage, meant that the flood water mixed with untreated sewage further hindering the clean-up (Corcoran, 2005).

In order prevent this kind of event impacting the city to such a degree resilience, measures must be identified, prioritised, planned and implemented. In terms of the water management system the selection of measures is dependent on a range of risk factors including the domain, the threat type and its expected impact, and the value of the system assets (Birkmann, 2006). Through this case study, technical protective measures are planned and implemented while measures needed to cover the related organisational and societal aspects are also explored.

This research began with the idea to conceptualize the STS as both an analytical construct representing the Dublin water management system and the unit of analysis for understanding STS resilience management. The envisaged study involves both deductive reasoning proceeding from general principles to understand a specific instance and inductive reasoning that derives broader generalisations about urban STS from observations of the Dublin case study. The study develops the conceptual RMF, consisting of resilience theory and other components of complex adaptive STS theory, to guide the analysis of the Dublin water management system. Through the study, the RMF tools are used to gather data to inform STS resilience management, which are validated by expert opinion.

Section 5.2 describes the case study area, followed by Sections 5.3 through to 5.8, which address each of the six RMF stages. For ease of reference, the six stages of the RMF are repeated here:

S1 Building resilience awareness; details how agents were informed about resilience through interviews, project work, team meetings, and consultation sessions.

S2 Selection of essential organisational components; this stage involved the selection of critical assets within the system.

S3 Disaster Resilience Indicator (DRI) assessment; the DRI assessment is designed to give a baseline resilience benchmark, which can be monitored as improvement measures are taken. Gathering accurate data for the resilience measures from the DRI assessment was one of the primary challenges faced.

S4 Prioritisation of vulnerabilities; the analysis of the output of Stage 2 and Stage 3 identified the vulnerabilities of the system, which could then plotted and acted on.

S5 Increasing the adaptive capacity; following the analysis of the vulnerabilities in S4, the process of implementing adaptive measures could begin. These included new technologies to improve the STS resilience by better informing agents at all levels of the STS of potential future threats and to give them advance warning in the event of a disaster.

S6 Recovery and reconstruction; the final stage of the RMF case study involved the identification of adaptation strategies and potential measures to retrofit the STS with resilience based tools.

The framework is comprised of six stages, which are underpinned by the DRIs. The discussion on the partial testing of the RMF focuses on the two major stages, which were realised during the case study (S3 and S5). The critical steps in the testing of the RMF were the DRI testing (S3) and the adaptive capacity improvement tool selection and deployment (S5). IoT-based flood sensors (described in Section 5.7) were the tools chosen to increase the adaptive capacity (S5) for the case, the selection and deployment process for these sensors is given particular detail in this chapter.

5.2 Study Area

Dublin is one of the five worst placed cities in Europe for flood preparedness (Guerreiro et al., 2018). The intergovernmental panel for climate change (IPCC) have said that climate change and extreme weather events due to heating of the climate system is unequivocal, (IPCC, 2014). Among the predicted adverse impacts that climate change will have are rises in sea level, more intense storm surges, high level rainfall events, and an increased likelihood and magnitude of river and coastal flooding (Economist 2017; EPA, 2008). As an island nation Irelands cities are primarily based in low lying river basins which are particularly vulnerable to rising sea levels. The viability of significant urban centres such as Cork, Dublin, Galway, Limerick, and Waterford are at risk (Halcrow, 2014). Furthermore, with the recent increase of population concentration in urban areas, a flooding disaster in these centres would have a magnified impact, as a greater number of people would be affected.

The impact of climate related flooding poses significant risks for all of the essential services on which our modern society depends. Critical infrastructure (CI) such as the

transport network, water supply, energy (electricity and fuel) systems, and communications services, are all at risk. The RMF is designed to be applicable to any STS type across transport, energy, water or health. The stages of the RMF will remain the same, although the specific steps may vary. Flooding is a primary concern for the water management system. In the initial conceptualisation, the case study area was intended to cover the same geographical district as the Dublin City Council (DCC) administrative border shown in figure 5.1.

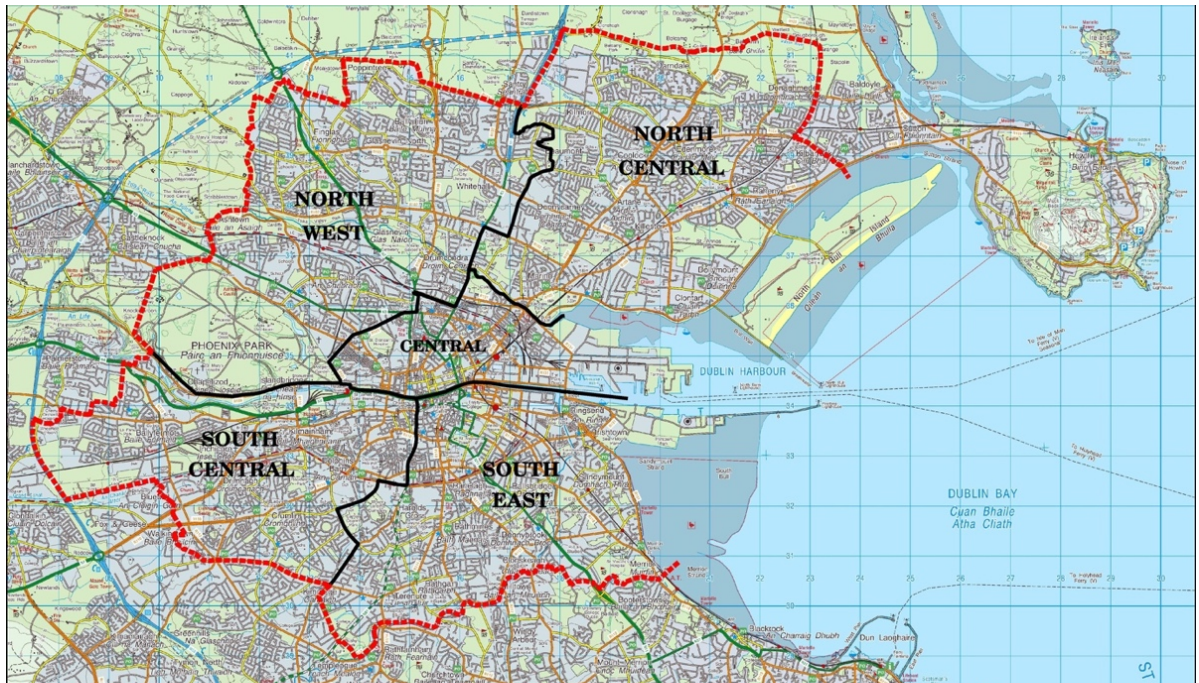


Figure 5.1 Case study administrative boundary area

The interview evidence and separate consultation with DCC staff led to a deeper understanding of current operations and the full extent of the STS. Although the experts agreed that the DCC boundary is of a valid size in terms of a manageable study area for an individual researcher, there were a number of important features outside of this area identified that should also be included. The case study boundaries should not be restricted to the red line outlined in Figure 5.1, rather, infrastructure outside the boundary, on which the system may be reliant, should also be included. Assets not necessarily within the administrative boundary that may affect the water management objectives of the region were therefore included as part of the STS analysis. The additional areas identified by the experts and further review included the rivers from their source, the entire arterial drainage network, and any other related infrastructure.

Figure 5.2 shows the arterial drainage map which extend well beyond the administrative borders originally selected.

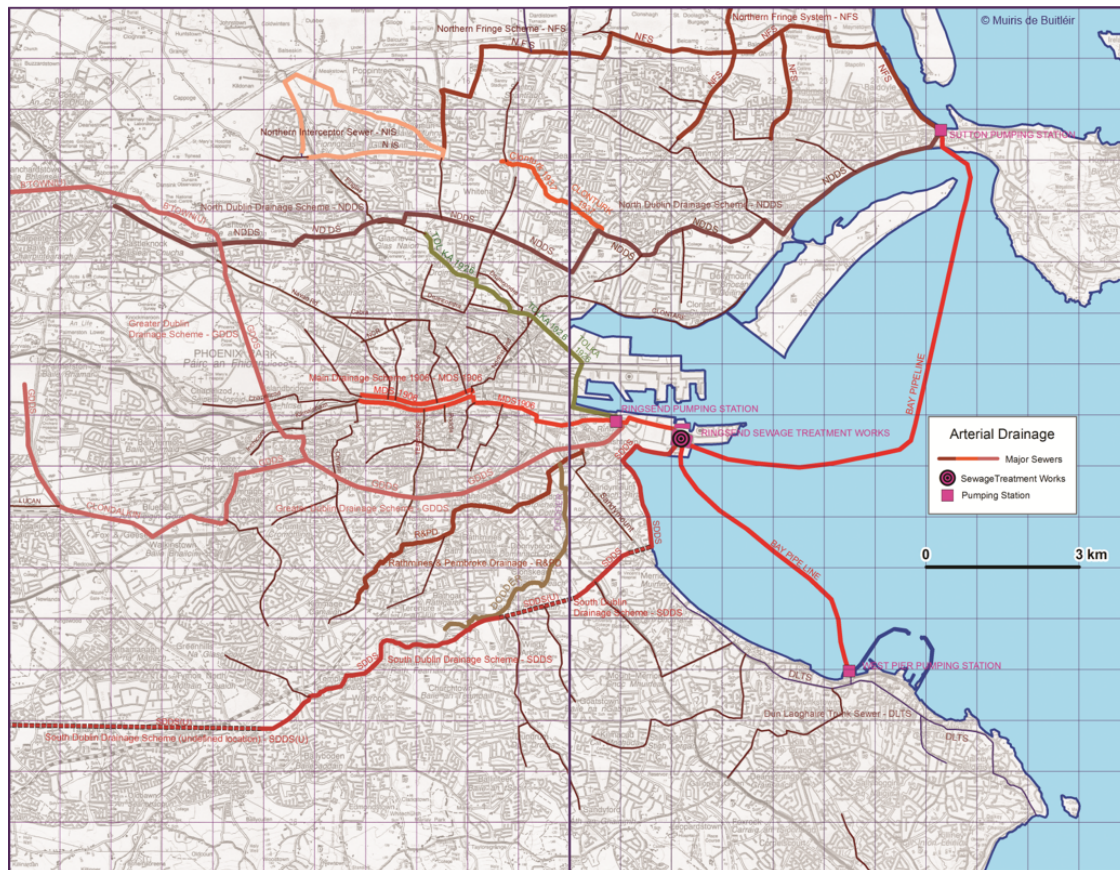


Figure 5.2. Arterial drainage map of Dublin

The academic panel in particular suggested that resilience should be examined from as large an area as is feasible, while being mindful of the increasing the complexity with a broader area. According to one member of the academic panel “...*resilience cannot be properly measured or improved when infrastructure and other features outside the administrative boundaries are excluded*”. The majority of the experts agreed that while the DCC border as shown to them in the questionnaire included the majority of the stakeholders who rely on the STS, the resilience analysis should also include aspects outside of the municipal boundary.

As a result of this insight, the spatial boundaries and scope of the STS were established by combining two sets of recognised spatial units and their boundaries. The case study area is shown as it appears in the Geographic Information System (GIS) mapping tool in Appendix F1. One of these is the DCC boundary, which is definable by the political-administrative boundary of the city (see Figure 5.1). The other set comprises of the

major rivers that flow into this area. The key infrastructure assets of the arterial drainage system, include the pumping stations in Dun Laoghaire and Sutton, which are outside of the DCC administrative boundary (See Figure 5.2).

5.3 Building resilience awareness (S1)

The national adaptation framework (DCCAE 2017) and Dublin City Development Plan (Council, 2016) highlight the need to improve resilience, however there is a limited understanding among flood management practitioners about the components that can be changed or the ‘levers’ for action that enable STS to recover more quickly. While there is general consensus of what urban resilience pertains to, and for the need to defend urban areas from disaster, there is less clarity on the precise resilience-building process. The literature to date has identified factors likely to be correlated with achieving resilience for STS, including conducting pre-event prevention activities, creating social media campaigns, educational websites to minimize the negative consequences of disaster (Godschalk, 2003); however, these domains have been rather broad and lack the specificity required for implementation.

In order to better understand the current issues and management hierarchies present in the STS exploratory meetings were held with Alan Vickers, the Chief Water System Technician in DCC, and Professor John Fitzgerald, who is the former head of the ESRI and current Chair of the National Expert Advisory Council on Climate Change. These initial exploratory meetings followed by consultation with DCC staff highlighted that the practitioners had little working knowledge with the concept of resilience.

The CFRAM programme identified that 95% of properties at risk within the communities assessed to be at significant risk from flooding can be protected by flood relief schemes (Halcrow, 2014). For the balance of these properties, and for other properties at risk outside of these communities, other structural and non-structural measures are already in place. Concerns were raised that water management services across the city are insufficient for larger flood events, which have continued to exceed the ‘one hundred year event’ benchmark. The scale of these events, which may not be capable of being contained, require resilience planning in order to mitigate their impact.

A resilient STS must be inclusive of the many local stakeholders that need to collectively anticipate and respond to disasters. This step involves fostering and embedding both participative and deliberative forms of public engagement in planning and decision-making processes. The approach of negotiating and defining shared vision of resilience between agents is necessary, but is not necessarily explicit. This is a primary concern where adaptation of plans is actually implemented. The expert interviews (Chapter 6) certainly addressed the needs of the stage objectives to inform experts and highlighted the communication issues between agents - both between levels of the STS and between agents on the same level, but in different organisations. Through these interviews, it became clear that competition between organisations has led to a breakdown in communication and, despite a high level of overlap between organisations, meetings are often only held annually.

In some instances, it may not be possible to reduce the likelihood or severity of flooding to an area at high risk. However, actions and measures can be taken to reduce the consequences of flooding, i.e., reduce the risk to people and of damage to properties and other assets, and ensuring that people and communities are resilient to flood events. This can be achieved by being aware of and preparing for the risk of flooding, knowing when floods are going to occur, and taking actions immediately before, during and after a flood. The actions and measures of this type include:

- Flood Forecasting and Warning;
- Emergency Response Planning;
- Promotion of Individual and Community Resilience;
- Individual Property Protection; and
- Flood-Related Data Collection.

In the first instance it was planned to explore possible routes to inform local stakeholders of flooding as a threat and flood plans through a website. While the building of awareness with the general public is key at this stage, as the shift to resilience was discussed it became clear that it was first necessary to inform and educate the decision makers themselves of the resilience concept and the management strategies available to them. A set of tools were needed to achieve an increased awareness of resilience issues among key actors; including semi-formal, open ended

interviews, project work, team meetings and reporting of observations from consultations.

Following research for this stage, it was found that Smart Dublin, an initiative of Dublin City Council and the other Dublin Local Authorities, had partnered with the TCD CONNECT Centre, a Science Foundation Ireland Research Centre, and INTEL to deploy low-cost sensors across the Dublin to monitor rainfall and weather conditions for flooding. The managers of this initiative were approached for a possible collaboration and all group meetings over the course of the case were attended. These meetings provided insight into the operation of the STS and current best practice for weather measurement and tool design, which were the desired approach of the experts for building resilience awareness both for the local stakeholder and also for the STS practitioners themselves.

This approach to sensor development is also being adopted by the Office of Public Works (OPW) and MET Éireann, who are also working to produce a rain prediction tool to inform decision makers of rain volume and the time taken for rain water to reach flood choke points around the city. This information may also be combined with the OPW flood catchment models. MET Éireann and the OPW operate river models to better predict key flood aspects for each local council, and these are combined with the CFRAM mapping output and ‘one hundred-year event’ historical data. Similarly, the IoT sensors developed as part of the case research (which are detailed in Section 5.7 below) contribute to educating the decision makers discussed here as well as local STS stakeholders through the flood alarm feature. When river levels rise to pre-set threshold levels, the sensors send out a warning to the user on the website, via email and SMS. Sensors were placed on a number of rivers around Dublin and, although further testing is required within DCC, the capability to warn local inhabitants and STS stakeholders of a flood ahead of time is now possible.

5.4 Selection of essential organisational components (S2)

This stage of the RMF is designed to determine the core assets of the STS, with the aim of aiding the development of suitable resilience strategies. The indicators outlined in

Appendix A, were developed to analyse the importance of the core assets based on their financial cost, and the societal impact the loss of functionality would have.

Extensive work had been carried out by the OPW, the Environmental Protection Agency (EPA) and Irish Water in the selection of assets related to the flooding and water management for the STS. Based on this work, it was decided that it would not be necessary to repeat this task using the developed RMF asset selection indicators. Furthermore, given the time constraints of the project and the labour intensity of the task it was decided to forgo the repetition of this stage and to adopt the assets already selected by the operating bodies.

Regardless of whether the asset selection indicators put forward in Appendix A or an existing selection process are used by the STS agents, the main point is that the selection criteria for the asset include:

1. Criticality to operations;
2. Preparedness for disaster; and
3. Susceptibility to an event.

By analysing the publications from the OPW, EPA and Irish Water, the essential organisational components were determined. In rank order are (1) the treatment plant in Ringsend, (2) the pumping stations in Ringsend, Dun Laoghaire and Sutton, and (3) the water pipe system itself are viewed as essential assets. This list was subsequently confirmed by DCC water management practitioners, who were consulted through the Smart Dublin flood project. These assets may be seen on the arterial drainage map in Figure 5.2. and the shape file on the Quantum Geographic Information System (QGIS) map can be seen in Appendix B under Infr24: Critical Assets

In addition to the primary service provision assets, such as pipes and pumping stations, and treatment plants being included, DCC water management staff also suggested secondary flood defence assets, which include river walls, locks and screens. Through the CFRAM study, the OPW have developed a Defence Asset Database. This database defines a defence asset as any structure that provides a flood defence function by preventing floodwaters from affecting local properties or land. It is important to note that for this database, structures are not considered to be defences if they are bypassed

by flood waters or would be unable to withstand high water levels in the event of a flood. A database for the defence assets is being prepared to collate details of the location, type and condition of all flood defences across Ireland. The focus of this work is on raised defences, and as such, the majority of the database will consist of raised walls and embankments along the banks of watercourses (Halcrow, 2014).

5.5 Disaster Resilience Indicator (DRI) assessment (S3)

The next step of the case details the application of the DRIs to the STS, which will provide a baseline measure of resilience. The resulting score provides decision makers with a resilience benchmark, which can be monitored over time as improvement measures are taken. The operationalisation of the twenty-four DRIs on the final list shown in Appendix B is a specifically designed decision support tool. The DRIs form the basis of a resilience score, which will provide spatial assessment, in addition to an empirical ranking of the most and least resilient parts of the STS.

The academic sources for the basis of each indicator and the sources of indicator data used for the case study are outlined in Appendix B separately. Although the social and economic indicator data was relatively straightforward to gather, this was not the case for the critical infrastructure (physical) indicators. The lack of data availability was a restrictive factor that was encountered. Irish Water for example are only willing to share risk and asset related information to funding partners and could not provide the information sought from them. Where the data was not available, secondary sources such as news articles or practitioner knowledge were used. If this was deemed unreliable, the indicator was not used for the analysis of the particular area. Combined primary and secondary data sources were available, such that all of the areas were included in the case and none had to be left out. The analysis may be updated where missing data becomes available. Where some of the data sources are non-numerical, a translation of the data was necessary so that it could be usable. This necessitated the use of a GIS mapping tool. The QGIS map software helped to visualise the different data sets and facilitated the comparison of overlapping layers. The GIS input may be viewed under the relevant indicator in Appendix B.

Once the raw data was collected, the data was normalised to give a score out of 100. All other values were scaled in between the minimum (0) and maximum (100) values. High levels of understanding of the local data sources was necessary to complete this task in a timely fashion. Due to the researchers familiarity with the data sources, obtaining data for the case this was a relatively straight forward process. However, for STS where data is not available, a certain level of expertise may be needed for design, implementation and management of data collection where this is not already occurring.

The DRI scores provide a comparative assessment of urban resilience for the 162 electoral divisions (ED) in the study area. The results were analysed using two approaches. The first is a GIS spatial assessment and the second provides an empirical ranking of the most and least resilient ED. Figure 5.3 is a GIS spatial representation of the disaster resilience within the study region. The DRI scores are mapped as standard deviations from the mean; the map highlights those EDs that are ranking exceptionally well or poor in terms of their disaster resilience. The EDs shown in dark blue are the least resilient whereas counties symbolized in lighter pink are the more resilient. The key showing the DRI score and corresponding colour is also displayed in Figure 5.3.

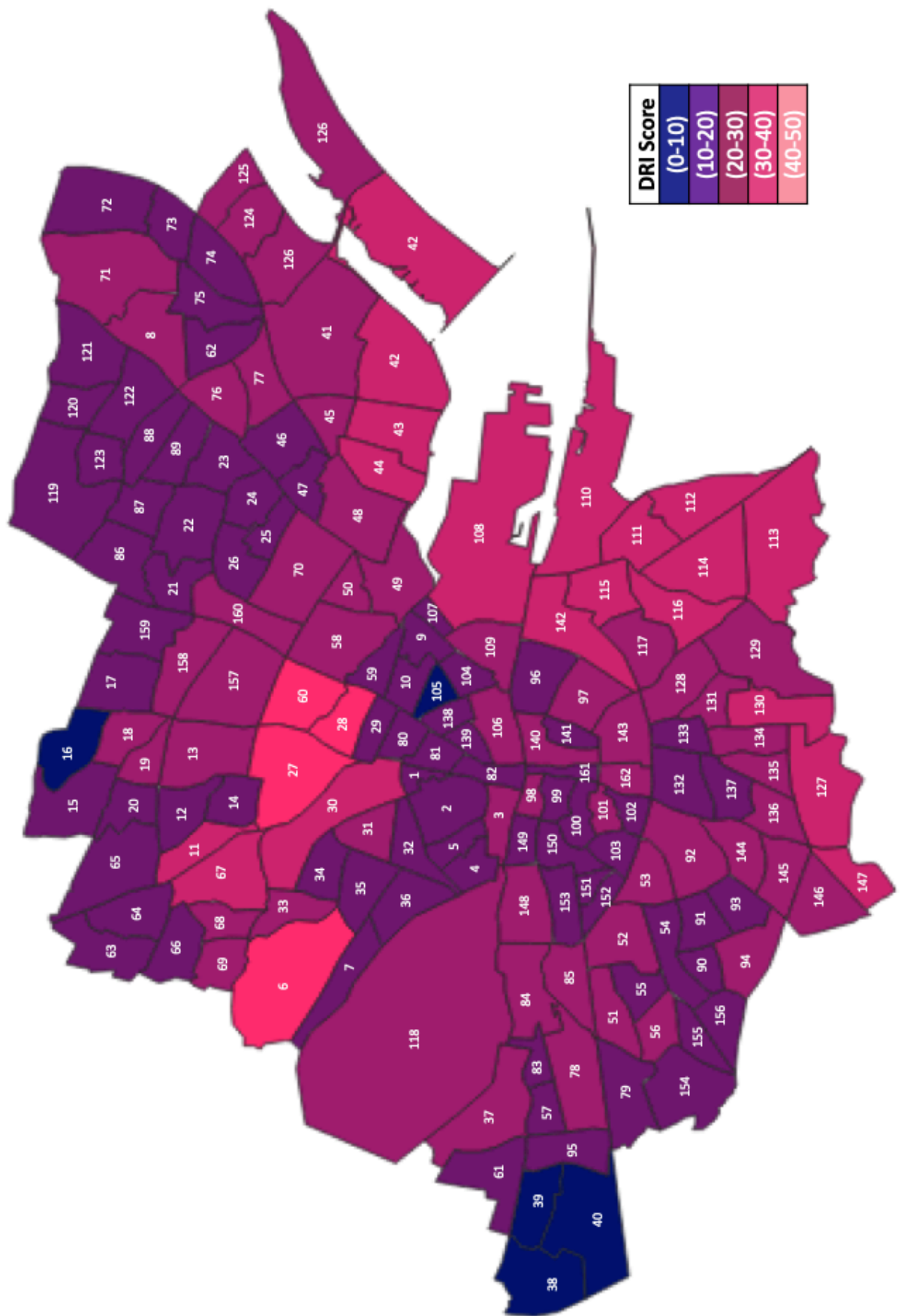


Figure 5.3 Resilience Scores Distribution Map

When the DRI scores are visualized in the form of the study or map, the geographic variations are evident. Wealthy coastal areas including Clontarf, Sandymount and Pembroke are all high-risk areas for coastal flooding and yet, high social scores combined with protective flood measures result in a high DRI score. Comparatively high-risk areas along the Liffey in the centre of Dublin and along the Dodder show much lower levels of resilience.

While the maximum DRI score is 100, no ED scored above 50, and this may be due to the high number of at-risk areas in the study area. The results show a noticeable difference in the north and south of the city. The north side EDs within the study area typically demonstrate moderate to low levels of resilience. EDs that break this include some of the least resilient EDs which are on the South side of the city. Cherry Orchard A, Cherry Orchard B and Cherry Orchard C are all EDs with low economic scores, but are also close to at risk areas on the river Liffey.

The outliers on the North side of the city, Ashtown A, Botanic A, Botanic B and Drumcondra South C, which all show high levels of resilience. Risk data for these EDs was not available during the case, and when they were contacted, the OPW stated that analysis is currently in progress. These scores will need to be reviewed once the CFRAM risk analysis for the river Tolka, which passes through these EDs, is complete and up to date data is available.

1	Arran Quay A	15.65	42	Clontarf East B	35.48	83	Kilmainham A	16.50	124	Raheny-Foxfield	23.43
2	Arran Quay B	14.34	43	Clontarf East C	32.47	84	Kilmainham B	24.93	125	Raheny-Greendale	22.38
3	Arran Quay C	22.84	44	Clontarf East D	30.48	85	Kilmainham C	23.94	126	Raheny-St. Assam	27.56
4	Arran Quay D	15.49	45	Clontarf East E	21.61	86	Kilmore A	18.05	127	Rathfarnham	31.05
5	Arran Quay E	16.70	46	Clontarf West A	17.63	87	Kilmore B	16.44	128	Rathmines East A	22.77
6	Ashtown A	40.36	47	Clontarf West B	18.42	88	Kilmore C	17.06	129	Rathmines East B	27.18
7	Ashtown B	16.04	48	Clontarf West C	25.71	89	Kilmore D	16.24	130	Rathmines East C	29.99
8	Ayrfield	20.55	49	Clontarf West D	26.69	90	Kimmage A	14.98	131	Rathmines East D	23.23
9	Ballybough A	13.36	50	Clontarf West E	20.26	91	Kimmage B	19.40	132	Rathmines West A	19.53
10	Ballybough B	14.45	51	Crumlin A	20.16	92	Kimmage C	28.08	133	Rathmines West B	19.67
11	Ballygall A	32.43	52	Crumlin B	20.73	93	Kimmage D	18.32	134	Rathmines West C	22.13
12	Ballygall B	18.49	53	Crumlin C	21.91	94	Kimmage E	20.74	135	Rathmines West D	21.87
13	Ballygall C	22.93	54	Crumlin D	18.79	95	Kylemore	11.30	136	Rathmines West E	20.31
14	Ballygall D	17.32	55	Crumlin E	15.49	96	Mansion House A	19.88	137	Rathmines West F	19.93
15	Ballymun A	12.43	56	Crumlin F	20.46	97	Mansion House B	20.52	138	Rotunda A	15.21
16	Ballymun B	10.56	57	Decies	10.13	98	Merchants Quay A	21.37	139	Rotunda B	12.03
17	Ballymun C	16.12	58	Drumcondra South A	23.38	99	Merchants Quay B	17.85	140	Royal Exchange A	23.72
18	Ballymun D	21.31	59	Drumcondra South B	18.99	100	Merchants Quay C	17.26	141	Royal Exchange B	17.40
19	Ballymun E	20.30	60	Drumcondra South C	44.81	101	Merchants Quay D	28.16	142	South Dock	33.15
20	Ballymun F	19.40	61	Drumfinn	11.26	102	Merchants Quay E	17.50	143	St. Kevin's	21.12
21	Beaumont A	16.58	62	Edenmore	17.62	103	Merchants Quay F	19.76	144	Terenure A	21.18
22	Beaumont B	16.54	63	Finglas North A	12.19	104	Mountjoy A	12.53	145	Terenure B	19.99
23	Beaumont C	16.00	64	Finglas North B	14.18	105	Mountjoy B	10.28	146	Terenure C	23.95
24	Beaumont D	15.51	65	Finglas North C	17.44	106	North City	22.04	147	Terenure D	30.04
25	Beaumont E	18.73	66	Finglas South A	11.55	107	North Dock A	16.11	148	Ushers A	28.26
26	Beaumont F	18.21	67	Finglas South B	30.86	108	North Dock B	31.27	149	Ushers B	19.65
27	Botanic A	39.96	68	Finglas South C	25.72	109	North Dock C	21.66	150	Ushers C	11.25
28	Botanic B	41.92	69	Finglas South D	27.93	110	Pembroke East A	31.02	151	Ushers D	13.41
29	Botanic C	18.22	70	Grace Park	22.23	111	Pembroke East B	33.15	152	Ushers E	16.69
30	Cabra East A	37.22	71	Grange A	22.85	112	Pembroke East C	35.71	153	Ushers F	18.53
31	Cabra East B	20.18	72	Grange B	19.86	113	Pembroke East D	31.98	154	Walkinstown A	19.87
32	Cabra East C	16.25	73	Grange C	16.64	114	Pembroke East E	37.83	155	Walkinstown B	16.29
33	Cabra West A	29.73	74	Grange D	18.24	115	Pembroke West A	32.15	156	Walkinstown C	15.92
34	Cabra West B	12.25	75	Grange E	16.39	116	Pembroke West B	36.46	157	Whitehall A	21.26
35	Cabra West C	14.64	76	Harmonstown A	23.16	117	Pembroke West C	24.33	158	Whitehall B	22.69
36	Cabra West D	17.38	77	Harmonstown B	22.52	118	Phoenix Park	21.47	159	Whitehall C	18.13
37	Chapelizod	20.02	78	Inchicore A	22.99	119	Priorswood A	18.73	160	Whitehall D	20.64
38	Cherry Orchard A	10.48	79	Inchicore B	19.81	120	Priorswood B	14.29	161	Wood Quay A	19.62
39	Cherry Orchard B	10.22	80	Inns Quay A	12.11	121	Priorswood C	15.74	162	Wood Quay B	20.24
40	Cherry Orchard C	10.83	81	Inns Quay B	12.88	122	Priorswood D	17.80			
41	Clontarf East A	29.93	82	Inns Quay C	18.72	123	Priorswood E	19.14		Average	20.96

Table 5.1 Resilience Scores

5.6 Prioritisation of vulnerabilities (S4)

This section outlines the linking of the results from the asset assessment is Stage 2 and the DRI assessment in Stage 3. Areas of significant vulnerability can then be prioritised and the selection of the appropriate strategy can be made. Information from the DRI assessment and the selection of essential components stages was analysed to identify those components that require an increase in their adaptive capacity and the appropriate intervention type. In terms of flooding, the primary strategies are listed here:

Flood risk prevention measures aim to decrease the exposure of the STS and its stakeholders via methods that prohibit or discourage developments in areas that are at risk of flooding. The main focus of the approach is on “keeping people away from water” by only allowing the development of the system outside flood prone areas. This is a proactive strategy that focuses both on probability reduction and on the consequences of flooding.

Flood defence measures aim to decrease the probability of flooding areas through infrastructural works such as dikes, dams, embankments, screens and weirs, mostly referred to as flood defences or structural measures. These options, which increase the capacity of existing channels for water conveyance can be maximised by increasing the space for water retention outside of the areas to be defended. sustainable urban drainage systems (SUDS) may be included in this measure as an alternative to traditional engineering approaches.

Flood risk mitigation focuses on decreasing the consequences of floods through measures inside the vulnerable area. Consequences can be moderated by smart design of the flood prone area. Measures include smart spatial ordering inside urban areas, water retention within the protected area or flood proof building. Flood risk mitigation thus includes all measures to flood-proof the built environment as well as measures to retain or store water. These measures may be outside the remit of the agents within the STS and may require interaction with local or national planning authorities. Alternative mitigation strategies include flood forecasting and warning systems, in addition to preparing disaster management and evacuation plans.

The baseline scenario is when the best course of action is to ‘continue with existing practice’ in terms of arterial drainage maintenance. This may be necessary due to the nature of current activities, and the uncertainty associated with damages that would arise should those activities cease. The baseline scenario may also be necessary depending on budgetary issues.

Analysis of the GIS map in Figure 5.3 above shows that river based EDs are the most vulnerable to flooding and scored the lowest in terms of their DRI score. The critical assets in these areas include the pipes in terms of the continued functioning of the

system, and the river Liffey and Dodder walls for flood defence. DCC staff concurred with the findings of S4 and commented that the choke point where the two rivers meet at Grand Canal Dock is one of the most high-risk areas in the city.

The output of this stage, therefore, recommends improvement in social and physical resilience of the STS in these areas through preparedness, awareness, structural and non-structural measures. The proposed measures (which are discussed in the next section) will enhance resilience of these vulnerabilities so the areas of low resilience will be better able to cope with the future flood hazards.

5.7 Increasing the adaptive capacity (S5)

This section details the measures, including IoT sensors, which were adopted to improve the resilience of the system based on the weaknesses identified by the DRI assessment. The DRI scores highlighted a number of areas with low resilience levels, which were geographically dispersed across the study area. The main assets in the areas identified were the water pipes themselves, in addition to the river embankments along the Dodder and the Liffey, which are difficult to reach and are seldom monitored. The general requirements for the solution include economic benefits of the intervention for a flood risk management measurement, which is calculated as the reduction in the economic damages the tool or measure will provide. The benefits should then be calculated assuming protection to the defined standard of protection.

Despite the findings of the DRI analysis, which highlighted particular areas of resilience weakness, there was no obvious ways to improve this as no form of measurement was currently in place to monitor the water flow, flood choke points or the capability of the flood prevention tools to perform. From the literature review and the feedback from experts on the ground, it became clear that more information was needed on where flooding is occurring, how long rainwater takes to reach different points on the rivers throughout the city. In order to ascertain what intervention could be used to improve the resilience in this way, the DCC water management engineers and other members of the Smart Dublin flood team were consulted. This consultation highlighted the main weaknesses in the system were a lack of data and an overreliance on anecdotal evidence and personal experience of DCC staff for decision making. The

lack of data on weather events is further compounded as extreme wind regularly prevents DCC sensor messages from being sent over cellular networks during storms.

A critical consideration in selecting a preferred intervention is cost. One tool may perform marginally better than another, but it may also cost considerably more. Flood resilience measures may be viewed as long-term investments, which must be economically viable, i.e., the economic benefits of a measure (reduction in flood damages) must outweigh the cost of the measure, to ensure value for money. This equation is called the Benefit Cost Ratio (BCR), which the OPW currently use for any investment plan under CFRAM. The BCR should be equal to or greater than one, i.e. a euro spent will save more than a euro in damages. A cost benefit analysis (CBA) is necessary to determine whether options meet this requirement. This analysis was undertaken to determine the economic viability of each option for the case.

The solution should provide a more efficient way to monitor river water or flood levels so that messages would automatically be communicated with decision makers, without the need for a permanent power source and a potential secondary aim communicating flood warnings with the respective stakeholders. A consultation call with market leaders Storm Sense in Florida led to the identification of potential solutions for resilience improvement including flood-monitoring sensors. Following an extensive review of available technologies, interviews and meetings with practitioners and DCC staff, the benefit of IoT weather sensors was clear. These sensors addressed the concerns outlined above, were more cost effective than alternative sensor types and furthermore the information available from IoT sensors may be used by decision makers at all levels of the STS.

5.7.1 Research and Intervention Selection

DCC have a network of rain gauges and river monitors installed throughout Dublin city. Some of the locations have both a river level and rainfall gauge installed. Currently, these sensors are being monitored by personnel in Dublin City Council offices, as well as having a simple ‘alarm’ system when sensors reach defined thresholds. Each of the sensor’s data history can be downloaded as a CSV file, which is defined by their data frequency. Reports are sent on 1 minute, 15 minute, 1 hour or

24-hour intervals. The CSV report files are separated by date, with each file containing roughly 6 months historical data. Some of the sensors data goes as far back as 2012. Each of the files contain just the recorded rainfall and/or river level and the date on which it was recorded. A map of the sensors can be seen in Figure 5.4 where blue indicates a rainfall sensor, pink indicates a river level sensor and red represents both. These sensors are costly to purchase and expensive to operate, which has been a factor in the overreliance by DCC in anecdotal evidence and personal experience for decision making.

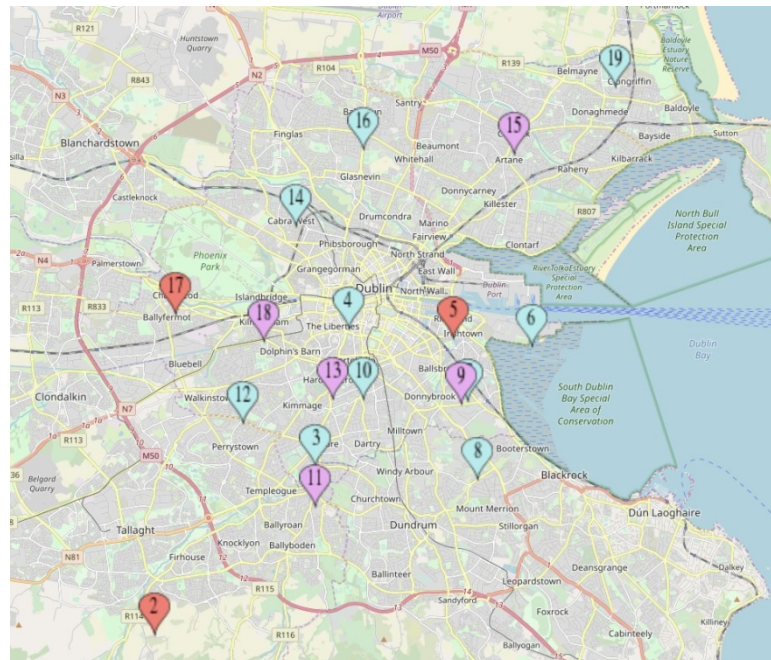


Figure 5.4: Map of DCC sensors.

Envisioning an appropriate resilient system requires the data that it reports to be accurate and reliable. The setup and the upkeep of the monitoring system also needs to be cost-efficient and easy-to-learn. Current methods used by Met Éireann and the OPW, in addition to newer projects and papers, which use IoT, are to be reviewed. Each will be evaluated in terms of their techniques, accuracy, cost, coverage, whether they require the involvement of expertise, and the availability of real-time data. Upon further review, a potential solution was discovered from Dunraven Systems, an Irish company based in Dundalk who manufacture the Apollo level sensor, which had recently been converted from an oil level reader to be effective on water. The potential of the Apollo in

comparison with the CONNECT sensors introduced in Section 5.3 and the DCC sensors is discussed here.

The Apollo CONNECT, and DCC sensors all use different networks for transmitting data to and from their platforms. The Apollo sensors use Sigfox, CONNECT sensors use LoRaWAN, and DCC sensors use SIM M2M. There is no specified network that must be used in an IoT system, as different types of devices and networks will suit different case specific characteristics. When choosing a sensor and network it should be noted that the communication type will directly affect the sensors hardware requirements and associated costs. A brief overview of an array of networks will be discussed in order to understand why and how different networks are employed.

Cellular Networks

Conventional cellular networks such as 4G and LTE are highly advanced radio systems, which use telecommunication masts (towers) dotted around the country to broadcast signals providing coverage. This communication type is capable of achieving high speed download and upload rates. The limitations of cellular technology for sensor communication is their high consumption of power, which requires a heavy duty power source for sensors. Cellular technology is also significantly more expensive than other communication forms.

IoT Cellular Network

There are two types of IoT cellular networks, one being a narrowband IoT (NB-IoT) and category M1 (Cat-M1) IoT (12). Both have very long ranges, with NB-IoT theoretically having a range of up to 100 km. A cellular network has the advantage over low power networks such that a user does not have to set up their own private network. Therefore, they are piggybacking on the cellular infrastructure that is already present.

Machine to Machine Sim (M2M Sim) is one commonly used IoT cellular network. The difference between a M2M Sim and a regular cellular Sim is that M2M Sim's are simpler – they can transmit a small amount of data, rather than voice clips. Because they are simpler, they are usually much cheaper than a standard SIM. The main benefit of choosing M2M over a low power network is that if a network goes down, an M2M sim

will simply switch and transmit data through another network. Low Power Wide Area Networks depend on the Internet to report data and each of the sensors have only one network to transmit data on. M2M SIMs are ideal for IoT systems where the data gathered must be sent without interruptions, thus M2M SIMs ensure the user will have a very small chance of all the networks being down.

Low Power Wide Area Networks (LoRa and Sigfox)

Low Power Wide Area Networks (LPWAN) is a type of wireless network that offers connectivity to devices, which require low power and transmit small packets of data at long intervals. The fact that it is low power makes it different to regular WAN, as WAN uses cellular technologies. Clearly, the issue of low power is very relevant in devices that use battery in circumstances where the sensors are located in areas that are difficult to access.

Both LoRa and Sigfox are companies that allow the configuration of devices to connect to LPWANs. The main difference between the two being that Sigfox itself is a network provider, while LoRa provides the technology (base station) to access a network. This means that some countries cannot use Sigfox as the coverage is not available but can use LoRa, as the user is able to establish their own base station network, this is ideal for small areas such as a farm or college campus but may be prohibitive for larger study areas. Both LoRa and Sigfox communicate with small data messages, which require low levels of power and have long-range communication of 10km and 30km radius to base station respectively. One data message may be sent every three minutes however, high rates of message communication will impact power usage and battery life. Although LoRa sensors are connected to the local base station, only Sigfox sensors may communicate with any base station in range. This is advantageous in an urban environment where a single message may be received by five or more base stations ensuring a built in redundancy to sensor communication. Due to the long range communication capability and the low levels of power required to operate, these devices are appropriate for use in a weather monitoring system as the sensors can be placed in remote locations.

5.7.2 Sensor Deployment

The Apollo sensors were adapted from their original function of oil level monitoring.

Testing of the original sensor was carried out by the researcher on a small local stream, which led to changes in sensor calibration, platform display and device housing, which were required before deployment on DCC sites could begin. The initial testing showed consistent message quantities being reported at the assigned intervals with no messages missed. During this initial six-week test, the battery loss on the sensors was less than a percent.



Figure 5.5: River level sensor deployment on the River Liffey

The sensors must be left in the river for long periods for trend analysis and so that relevant level readings for accurate threshold levels may be set. Sigfox technology is the most energy efficient form of connectivity available with batteries in Sigfox-enabled devices capable of lasting up to 300 times longer than those in cellular modules. The Sigfox network in Ireland covers 97% of the country, making it ideal for river locations at source in remote areas where cellular reception can be an issue. Each sensor speaks directly to one or more base stations, so no pairing or setup is required as the sensors are deployed. The Apollo sensors can also be used to set thresholds that can be used to warn for over consumption in reservoirs, leaks or for ordering in more water supplies in the event of a drought.

Deployment site selection for the sensors was discussed at length with DCC water management staff. Based on an analysis of historical flood locations and input from Alan Vickers on the local bottle necks, a series of primary sensor locations were chosen along the Liffey, the Dodder and the Tolka, in addition to some smaller streams and tributaries that are prone to flooding. Once these primary flood sites were selected, a corresponding site upriver was selected to monitor how long rain fall takes to reach the city from source. These upstream and downstream pairs were critical for analysis and predictive measurement going forward.

At this stage, the deployment of the sensors was stalled due to a high level of permission required from DCC and the OPW for the use of their sites. In addition, some of the upriver sites pertaining to the case study area fell outside of the DCC administrative boundary and so further permissions needed to be applied for from other surrounding councils. Once the appropriate permissions were received, the researcher along with DCC staff deployed a network of the Sigfox sensors. 11 Apollo flood level sensors were deployed on streams and rivers, including the river Liffey, Dodder and Tolka, a map of the sensors, as displayed on the Apollo dashboard, can be seen in Figure 5.2.



Figure 5.6 Sigfox sensor deployment dashboard display

On the above map of the Apollo deployment dashboard, the sensors are displayed with green markings. All of the devices were installed in February 2017. One of the sensors has failed, sending its final message in March in 2018. These sensors are a first step towards the development of a complete flood warning sensor network that will inform STS practitioners and nearby inhabitants of these rivers of flood warnings, which in turn will help minimise danger of lives and the damage to the STS.

5.7.3 Sensor Evaluation

To analyse the data from the Apollo sensors, in collaboration with the Smart Dublin flood consortium graphs were generated for each available sensor types in Dublin including CONNECT, DCC and Met Éireann sensor data. These graphs allowed for the interpretation of the relationships that exist between the different datasets. Analysis was carried out as part of the Smart Dublin flood project by the researcher together with colleagues in CONNECT on the Sigfox river level sensors and compared with existing DCC sensors. Pearson's method of computing the correlation coefficient r between the variables was used to define the relationship (Sharma, 2005). This involved plotting the levels of each of the Apollo sensors to examine whether there were any outliers and to investigate if data was not reported at a particular time. A graph was also made to indicate how many reports each sensor submitted. The Apollo sensors were then compared with the nearest DCC sensors on the same river/stream to establish if there was a correlation between them. The OPW data was then compared with the closest DCC and Apollo river level sensor.

Appendix E (E1-4) show the river levels of a selection of the Apollo sensors to demonstrate the vastly different water levels within a relatively small geographic area. The figures show two pairs of up river and down river sensors for the Liffey and the Dodder. The Liffey readings in particular had a high level of correlation between the paired sensors. Despite the malfunction of the Ballsbridge sensor readings they are included to show how predictability is negatively impacted as the Dodder is affected by tidal currents. The tidal extreme high tides before the Ballsbridge sensor ceased functioning suggest that the sensor may have been submerged in salt water for a prolonged period which would have damaged the hardware.

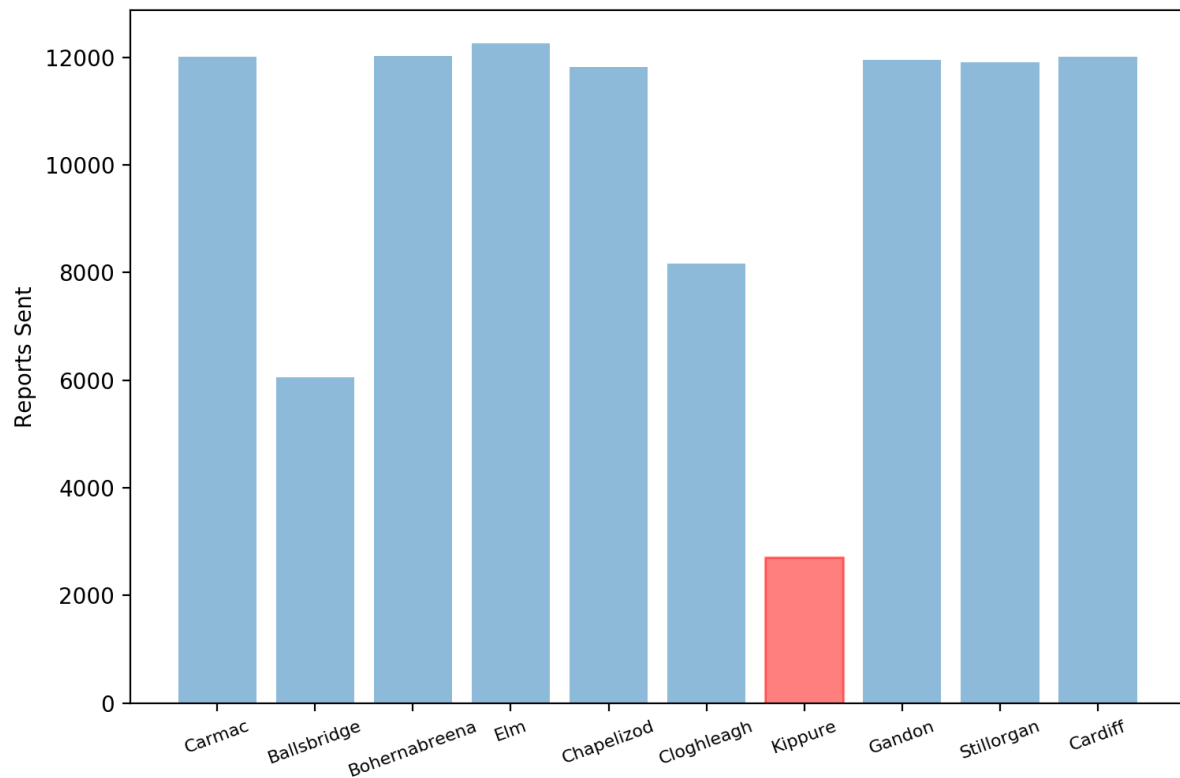


Figure 5.7 Sensor Data report volume

Figure 5.7 shows the total reports from each of the Apollo sensors. These sensors are configured to send data either every hour. This graph is promising in terms of the reliability of the sensors used and Sigfox network. The Ballsbridge based sensor ceased functioning in November 2018. The cause of this is unknown but due the tidal activity it is assumed that salt may have interfered with the hardware. The Kippure sensor, highlighted in red, ceased reporting data in February 2018 just two months after being deployed. Despite being bolted to a stone wall, the sensor was washed away by high volume snow fall (which also broke nearby car mirrors and barbeque sets). Less than 3,000 reports were sent by the Kippure sensor.

The DCC and Apollo river level sensors also had high correlation, however. Overall, both Apollo and DCC river level sensors had positive results and it could be suggested that they can be used in a real-time flood monitoring system.

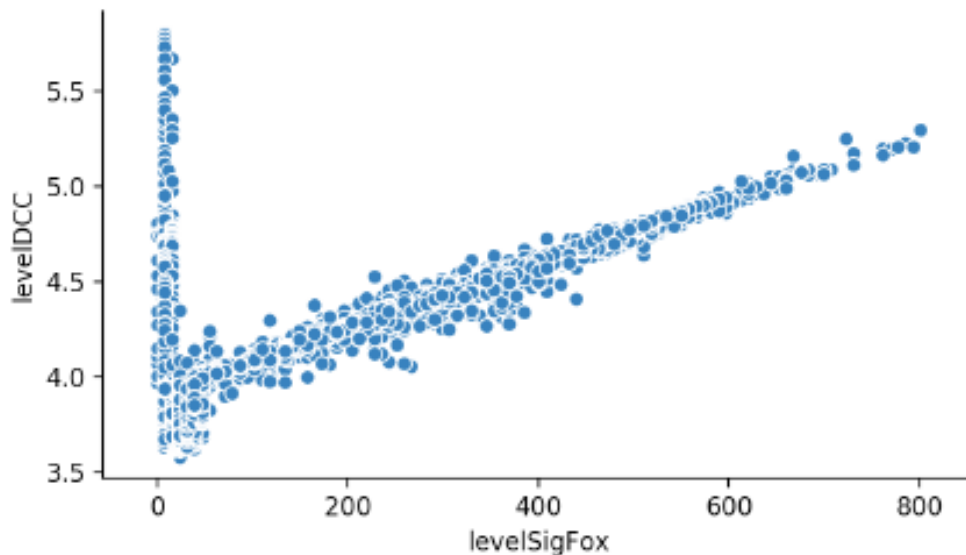


Figure 5.8 Pairplot of DCC and Apollo for the River Liffey Sensor

In terms of networks, the Sigfox network is quite reliable at sending data when compared to traditional cellular communication. This was evidenced by both the Apollo and DCC datasets having little missing information. Comparatively the CONNECT sensors on the LoRaWAN, are not sufficiently reliable and often days elapsed where no information had been reported.

As a result of this collaboration with the Smart Dublin flood project, the flood sensor data is being made publicly available on the Dublinked data-sharing site. End users can check river levels online while local authorities and municipalities will benefit from the profiling data that is so important in understanding river and tidal behaviour in real time. The value of the results and data coming from these sensors has been recognised by their use on the UCD OPERANDUM project as well as being the subject of a master's thesis.

5.8 Recovery and reconstruction (S6)

Beyond restoring functionality to the CI within the STS, the focus of recovery should be to help local communities to thrive rather than just cope with disaster. Implement adaptation strategies and retrofit the STS with resilient materials. Over the duration of the case study no major disaster event occurred and so there was no opportunity to investigate this stage of the RMF.

During S6 the agent's goal is to implement adaptation strategies to restore the system's core services, preferably enhancing them above the pre-impact level, and to minimise any break in service where possible. The governance of STS requires decision making which goes beyond the scope of any individual actor so recovery plans must take the input of agents across levels of the STS into account.

A successful recovery will be efficient, timely and should improve the system overall. This can be achieved by retrofitting new adaptive complex management structures; facilitating the capabilities of the system to respond and recover. 'Reconstruction' has the aim of learning from the event and feedback loops thereby improving resilience for the next iteration of the process.

The case study explored the possibility of IoT sensors being appropriate for use in river flood monitoring. In this regard, there is still work to be done in order to establish this proposition. Once the accuracy and the quality of the data being reported is ensured, more sensors would be placed around Dublin. For the most part, flooding can occur anywhere in Dublin and, in order to get the best overview of the city, more sensors will need to be installed. The future recovery and reconstruction of the water management STS should include the development and deployment of different IoT sensor types displayed on a single dashboard capable of analysing rain, river and tide levels to warn STS agents and stakeholders of oncoming flood risk.

5.9 Summary

Chapter 5 demonstrates the partial testing of the RMF in the Dublin water management STS through the case study. While each stage of the RMF is detailed the case study highlights the importance of S3 the DRI assessment and S5 increasing the adaptive capacity of the RMF through the introduction of IoT sensors to the STS. The implications of these results are explored through the findings in Chapter 6.

A lack of data for decision making is a major issue in infrastructure management in Ireland, the value of this case study is the sensor data and the demonstration of how this can be used going forward. Provisionally the network of 10 IoT flood sensors, which were deployed in the case can be viewed as a proof of concept for further sensor

network expansion. The accuracy and performance of the sensors was demonstrably accurate with results consistent with the current DCC sensors.

These types of smart sensors provide a low cost and efficient way to protect against flood damage. The low-power and long-range of the Sigfox network allowed the flood sensors be deployed almost anywhere along Irish rivers and as a battery powered device they can be left in situ for constant level monitoring for years on end. Data collected from the sensors can provide vital information in relation to the behaviour of our rivers, how they flow and how these flows are affected by rainfall. Past heavy rainfall events can be analysed to reveal the effect on water levels at various points in the catchment. When used as a predictive tool, this data will allow authorities and individuals to react pre-emptively, rather than reactively, to predicted heavy rainfall. There remains however, an issue with lack of understanding of IoT and introduction of new technology led to competition and an unwillingness to change.

CHAPTER 6 FINDINGS

With the case study presented in the last chapter, the Resilience Management Framework (RMF) was trialled and demonstrated the requirements necessary to quantify a baseline of resilience and the challenge of trying to alter the system with the introduction of new tools and technology. The case study was influenced by the information elicited from the expert interviews, which took place over the course of the case. The findings from these interviews are presented in this Chapter.

6.1 Introduction

The urgency of developing urban strategies for coping with changing environmental and socio-economic conditions has inevitably led to an increase in resilience research. The literature review highlighted how broad the range of urban issues are from a resilience perspective, and how significant the impacts of these can be on local inhabitants of the areas affected.

In the first instance, the interview process was designed to answer the initial research questions that guide both the research process in general and the practical case study of resilience in Dublin. Quite simply, the information sought is related to the questions asked in Section 1.3. Secondly, the interviews investigate the validity of the RMF outlined in Chapter 4. Thirdly, the interview is designed to elicit current knowledge gaps (if any) among the experts which may facilitate the use of the RMF in practice, such as determining the information required by potential end users, and the context in which it will be used etc. I judged such information based on (1) my experience regarding urban resilience gained while working on the Realising European Resilience for Critical Infrastructure (RESILENS) project; and (2) informal discussions with (former) colleagues and acquaintances from the RESILENS project, Dublin City Council (DCC), and Trinity College Dublin. Fourthly, the questions are designed to elicit the type of information needed to complete an in-depth analysis of resilience in terms of flooding in Dublin and to ensure the validity of the information collected: observable facts, written material, graphic representations, expert opinions, etc. These various forms of information formed the basis on which the analysis is performed. The complexity of STS and the cities in which they are contained require description prior

to measurement, and so the scope of the case study must be carefully selected (Baxter and Summerville, 2011).

6.2 Interview Analysis

The interviews involved experts from a range of distinct backgrounds. The purpose of the interviews is not to simply identify commonalities between them or point out how they are distinct, it is to gain a better understanding of the range of (management / policy) dynamics that are present when it comes to determining the resilience of STS operations and to inform the design of the RMF to ensure the practical application and usability of the tool for potential end user decision making. The support of these and other stakeholders are needed for the successful embedding of urban resilience tools in future urban management. This section elaborates on some of the recurring themes that have been identified in the course of the analysis of the interviews as well as on other topics that emerged, which could constitute potential future avenues of research. While responses are left anonymous, through this section general responses from the academic, political and practitioner groups are contrasted.

6.3 Understanding of and approach to managing urban resilience

A “stakeholder based” resilience approach to flood management is preferred by the majority of interviewees as opposed to current risk management approaches. Resilience is accepted as a concept that management and policy makers alike could easily understand and adopt. The academic interviewees in particular communicated a (hopeful) view that the concept will be successfully adopted to mitigate the damage caused by disaster events.

A significant majority of the interviewees express a view that resilience is the optimal approach to disaster management. Possibly because of its relative new introduction in the urban management arena, resilience has not yet been explicitly structured into tools and policies as much as ‘sustainability’, hence the expectation that it could represent something new. It was agreed that resilience should be integrated more; a number of the management experts outlined how they have planned to implement resilience measures. Indeed, some of the management interviewees identified the use of a resilience perspective in current risk approaches, albeit using different labels and terminology. In

some cases standard risk approaches were misidentified as resilience approaches and in two cases the various interpretations of resilience signal a misidentification, and a struggle to recall any resilience approaches in practice.

The academic panel were very familiar with the current literature on urban resilience and acknowledged the shift from earlier resilience thinking, which aimed to improve resilience for any possible event at any possible time, to a more practical approach. They agreed that by identifying the most likely disaster event to impact the STS, a resilience plan designed for this particular event could be more realistically applied.

6.4 System Boundaries

Adopting physical boundaries may be necessary for a study and especially where resources may be limited, but the point of resilience is that it exceeds physical boundaries. The selection of the DCC boundary as the case study border was explained in Section 5.2. Although the experts agreed that the DCC boundary is of a valid size in terms of a manageable study area for an individual researcher, there were a number of important features outside of this area identified that should also be included. The case study boundaries should not be restricted to the red line outlined, infrastructure outside the boundary - but on which the system may be reliant - should also be included. Resilience cannot be properly measured or improved when infrastructure and other features outside the administrative boundaries are excluded. Assets not necessarily within the district, but which may affect the water management objectives of the region, should be included. The areas identified by the experts included the rivers from their source, the entire drainage network, and any related infrastructure. As one panellist explained “when measuring resilience, the system boundary should be as all-inclusive as possible”. The academic panel in particular suggested that resilience should be examined from as large an area as is feasible, while being mindful of the increasing the complexity with a broader area. The majority of the experts agreed that while the DCC border (as shown to them in the questionnaire) included the majority of the population who rely on the critical infrastructure (CI), the resilience analysis should also include aspects outside of the municipal boundary.

It is agreed that any framework which aims to benchmark and monitor resilience should primarily focus on the inhabitants who rely on the system rather than the physical infrastructure alone. There is a consensus that this issue had been generally ignored by practitioners and policy makers to date. The issue of interdependencies and interconnectedness of STS across spatial scales is acknowledged although the understanding of this varied between the interviewees. There is a consensus among the panel that the 'system' should include the infrastructure within the DCC administrative area, the local communities and the rivers which run outside of the study boundary.

As part of the system boundary, secondary systems on which the water network relies were deemed important by the panel and should also be included. In terms of a secondary system a number of infrastructures were suggested, including energy, transport, telecommunications, and health. The impact of disturbances, should not be restricted to physical impacts alone, the economic fallout should also be included in the case study. How external and physical factors impact the social and economic domains is also deemed critical for resilience. Physical, social and economic domains will all depend on the budget made available to improve the resilience of an area. The academic panel highlighted the benefits of systems thinking and identified feedback loops as key to improving the resilience of a system over time.

6.5 Social and political landscape

All of the experts agreed that flooding is the major climate threat facing Ireland and despite this, it was acknowledged that the general public are not aware of the level of the threat posed. At present the public may be informed of a major flood event as it occurs through the media and press release. However, how to protect their homes or where to evacuate is not widely known.

The key groups influencing how flood management policies are being designed in Ireland are the civil servants groups, including the Office of Public Works (OPW) and the consultants that they hire, who are able to influence policy. Local civilians who are not politically vocal may receive a lesser service in their area in comparison to areas with a more engaged community. The experts agreed that a wider group of stakeholders should be included in the resilience of cities. Divergence between experts from the

management practitioners and the political groups was stark in the opinions on which groups should be included in the resilience management process. The practitioners were concerned solely with the supply and management of water, which is the goal of maintaining system functionality. The political group were more focused on the need for elected government oversight and the inclusion of local inhabitants' views / considerations. The RMF approach adopts the view that the resilience of the system involves the continued functioning of core services in the event of a disaster event but also the inclusion of other stakeholders.

While the experts agreed that a wider stakeholder group should be consulted for resilience management, the necessity of a common language was also raised. The management and political panels highlighted the need to communicate the issues affecting the STS and their plans to address these issues with the general public. One member of the academic panel suggested that without a common understanding of the issue and action plan by actors within a system, resilience cannot be achieved.

Each of the academics, management practitioners and the political groups highlighted the Dublin Climate Change Action Plan (draft plan) as being key for resilient management in the city going forward. The plan suggests bringing the four Dublin regional authorities together in a more cohesive way to manage flood resilience. For DCC specifically, 40 different actions are put forward including the use of sensors on the rivers and linking these with the CFRAMS for assessment and management. The suggested Action Plan options are closely aligned with the RMF approach outlined in Chapter 4, however, the plan is designed for the local authorities only and so excludes any aspect pertaining to infrastructure management outside their purview (OPW or Irish Water).

Two members of the academic panel independently raised the issue of how resilience planning should be funded. If a budget is unavailable in advance of a disaster event and only in place after the event (i.e. a disaster relief fund), the impact of physical disturbances will be more profound. Currently in Ireland individual bodies have their own government appointed budget which they are free to manage, there is no overall resilience or risk budget. It is the expert's view that a resilience budget should not be

seen as a stand-alone aspect and should be available to improve resilience in line with the threat of physical disturbances.

6.6 RMF feedback

Although the interviewees generally held the same understanding of urban resilience, there is no consensus among on how resilience should be embedded in managerial approaches to flood management. Consequently it is important that resilience is clearly defined and integrated along with current staff experience to help to promote and apply resilience in practice in the RMF. Despite the divergence of views on its meaning, there is recognition among the majority of interviewees that resilience can be quantitatively measured.

The experts were given an overview of the RMF approach with specific details on the Disaster Resilience Indicators (DRIs) and the Apollo flood sensors. Although most of the interviewees were enthusiastic and positive in their feedback on the RMF, a small number of concerns were also raised around linking the prosperity of an area with its resilience. There was also a hesitancy among some of the management officials about how a framework of this nature could be applied in line with current practices. Indeed, during follow up questions it was suggested that a culture exists across the flood management bodies that actively prevents the development of alternative management approaches. This culture reinforces the value of experience and traditional hierarchy over new technological interventions. Attempts at innovation or the introduction of new solutions are further frustrated by the level of bureaucracy and paper work required for new projects (examples of this are further explored in Chapter 5, where ‘ladder use training’ and the wearing of a life jacket in a shallow stream were mandatory). The experts were anxious not to name specific personnel responsible for sustaining this culture, but an ‘older generation’ of civil servant who were in conflict with their more junior colleagues were described by the management panels.

There also exists a hesitation amongst the interviewees to accept the results of any qualitative feedback, with quantitative measurement being preferred and believed to be more effective. Despite this hesitation, the management panel acknowledged that there

is a reliance on qualitative knowledge in current decision making processes. Therefore, the RMF should be sufficiently flexible so as to avoid a prescriptive approach.

Whether qualitative or quantitative, the measurability of urban resilience is essential to verify its good performance. Measurability ensures effective design and impact measurement of future interventions. Resilience frameworks and standards can provide a baseline onto which assessment for effective resilient improvement can be measured. However despite the complete support of the experts for an RMF type approach establishing the long-term functioning of a numeric based framework may be complicated.

The literature review (see Chapter 2) acknowledges that quantitative criteria in the form of comparative indicators are preferred by practitioners for resilience measurement and this was reiterated by the management panel. Criticisms of indicator-based solutions and ratings point to shortfalls implicit in their structure and the availability of data to ensure that the indicators are up to date. The rigidity of their assessment can lead to restrictive resilience approaches and working to improve a single indicator score may be counter intuitive to improving the resilience in the long run. Any resilience strategy that is indicator score based should also take practitioner experience into account. In formulating resilience guidelines, such a relationship needs to be elucidated, set in a correct perspective through the application of local knowledge and based on local factors as much as possible.

During the interview each of the DRIs were discussed and the relevance of each one to urban resilience examined from the experts' perspective. This was mainly concerned with the positive and negative weightings of various indicators, the specific types of tools used to improve resilience and how they can be incorporated with current tools or frameworks. Feedback from the experts on specific DRIs included the scale and scope of individual indicators, the availability of data, and the ability to compare regions. This feedback was taken into account and the RMF was edited where appropriate for the final draft.

6.7 Resilience management approaches

The majority of the panellists acknowledged the impact of climate change on the increase in heretofore unseen extreme weather events that are becoming the norm and the impact these will have on Ireland. However the area of greatest divergence among the expert panels was around the approaches of how to mitigate the impacts of climate disasters. Resilience management is perceived by the management panel as one that deals with ‘physical features’ (i.e. to be addressed through technologies and building techniques), and by the academic and policy panel with design that connects primarily with social and contextual conditions. In pursuing resilience, the management practitioners were almost solely concerned with the physical aspects of resilience which was linked with a more traditional risk based approach. The academic panellists suggested a more holistic approach to resilience, in line with the RMF design, which is more inclusive of the wider community. The political panel had a range of suggested approaches and while they agreed that local inhabitants should be made aware of the main issues in the city, they were less clear on how they could be included in the RMF type of approach. This suggests that there is a need for the RMF to clearly outline how the merging of aspects of each of the suggested approaches can be achieved: one that relates to physical preparedness to extreme events, and that also attempts to endow citizens with an understanding and engagement with the systems that they rely on.

The engineering panel identified weather event prediction tools as the main tools used by CI management in flood mitigation, and these are necessary for short term prediction and long term prediction capabilities to improve the resilience of the tool. River level sensors may be used for reliability is the key issue. Policies that are dependent on data coming from sensors requires that the sensors have demonstrated their capability and proven track record before being relied upon for decision making.

Nature-based solutions (NBS) such as sustainable urban drainage systems (SUDS), retrofitting tree pits, integrated constructive wetlands, retention ponds, permeable paving, green roofs, and other green infrastructure, were pointed to by a number of the experts as potential resilience approaches. These NBS offer an effective alternative to traditional engineering methods but despite being readily available and their relative affordability, NBS have not been deployed in Dublin. Green roofs in particular are seen

as especially effective, but when asked where these have been established, only one in Ballsbridge was pointed to.

The political panel highlighted the importance of communication tools for the dissemination of knowledge with the general public and explained that there is a disconnect with how systems work and the public's understanding of same. They suggested that engagement with the public should be a simple task. Emergency plans for what to do in the event of a flood are not known among the general public. There is a divergence of understanding between infrastructure managers, policy makers and the public who the system is designed to serve. The primary mitigation strategy suggested by a majority of the experts was the need to include the general public in the decision making process in the first instance by informing them of the issue of flooding. However the political panel also issues around the water management system consistently above the max operational capacity, stating that '*solutions are dogged by NIMBY-ism*'. This comment was made in light of the planned secondary water treatment plant at Clonsaugh being deferred following a high number of complaints by local objectors.

6.8 Summary

Chapter 6 presented the methodology and the initial results from the interviews of 13 experts from three different knowledge domains related to flood management, each with differing goals and objectives, organisational structures, cultures and processes. What follows is a summary of the findings from the interviews as well as their relevance for the purpose of the thesis. These findings complement those from the literature review in Chapter 2, namely:

- Conditions for resilience should be determined according to clear objectives, and the possibility of cities to adapt should be designed with those in mind. Benchmarks and numeric values are important only if these are clearly understood and pursued in line with existing experience and local knowledge;
- Resilience should be pursued at as broad a level as is feasible. It cannot be confined to the idea of a city's geographic boundary;
- The wide array of actors within an STS necessitates that a common language and clear communication between them, and with the public, as the first step in establishing resilience;

- Resilience should be considered from both an infrastructure and societal perspective (at least from some experts' perspectives). A resilience-based governance approach should include people in the decision making, make people aware of the strategies, and design of the systems should be done with these people in mind;
- Designing for resilience requires a focus shift from improving the general resilience of a city for any disaster type to a more focused, disaster specific (in this case flooding) resilience. As is illustrated in Chapter 5, the application of the RMF to a case study requires a specific CI and a probable disaster event and designing the case to respond to them;
- In order to make informed decisions tools that provide data are critical for any modern city, weather prediction tools, NBS, and communications tools were identified as priorities; and
- Finally, as the nature of resilience is systemic, any tool for its assessment should reflect this. Thinking in terms of systems can help identify feedback loops, links, and points of leverage. This in turn can facilitate the identification of strategies to improve the city's resilience over time.

These findings define the features that the case study and the evaluation method for resilience should possess. The interview data was consulted throughout the design and management of the case study as detailed in Chapter 5.

CHAPTER 7 CONCLUSION

This chapter summarises the key findings of the thesis; it reflects on the methodology and other aspects of the Resilience Management Framework (RMF) development and case testing; before identifying the limitations and contributions; and making suggestions for future research.

The chapter is organised as follows: Section 7.1 is the chapter introduction and overview. Section 7.2 reflects on how the research questions were addressed through the development of the RMF. Section 7.3 gives an overview of each of the chapters in terms of the research approach, conceptual framework, research design and strategy, methods and conceptualisation of the case study. This section also discusses methodological issues including bias, data quality, ethical considerations, validity and generalisability. The limitations of the study are outlined in Section 7.4. Section 7.5 summarises the findings and overall contribution of the research. The Chapter is completed in Section 7.6 with the recommendations for future research.

7.1 Introduction

The primary output of this research is the conceptual RMF, which is designed to combat the environmental impacts of climate change on STS with an alternative management paradigm. The RMF merged the theoretical urban resilience concepts described in Chapter 2 and the specific tools and experience of the expert practitioners and practical research. Furthermore the RMF provides a coherent structure for relating, organising and synthesising a diversity of assumptions, concepts and models grounded in resilience theory and which can be used to improve the response of STS to future man-made or natural disasters. The RMF combines STS theory and urban resilience theory which were integrated through each iteration of the framework over the course of the research. The RMF design struck a balance between the specific needs of the critical infrastructure (CI) in Ireland and general applicability so that in the long term the framework may be adapted and applied in other European Union (EU) contexts. Modifications to the RMF were made based on the literature review, which was a continuous reflective process for the duration of the research, the expert interviews and the from the results of the case study. Through the case study the RMF performed its

function very satisfactorily such that the engineering team were interested in further research and how it could be incorporated to their risk plans..

7.2 Findings

7.2.1 Addressing the Research Questions

The literature reviewed offered much guidance on how to improve the resilience of the urban environment, expert opinion was sought to validate these insights and to understand how to integrate resilience into management best practice. Although the expert practitioners interviewed had a similar understanding of resilience, their understanding of its application varied depending on their field of expertise. In particular, the traditional view of resilience being an extension of traditional risk and relating only to the specialist built environment was common. Although the panel were eager to improve their understanding and attitude to resilience, tools and approaches are necessary to ensure this is structured. Section 2.6 of the literature review explores the resilience analysis methods which thoroughly addresses RQ1. *'How are resilience analysis strategies currently being employed in conjunction with STS?'* The experts were aware of the limits of traditional risk analysis with regards to the primary concern of STS design and delivery, which is being negatively impacted due to the rising sea levels. However, despite the growing number of frameworks and analysis strategies available, practitioners remain reliant on traditional risk based tools. This was highlighted through the expert interview process and with the Smart Dublin flood project where although the concept of resilience was familiar, potential pathways to its application remain unclear for practitioners.

In response to RQ2. *'How can the resilience of STS be determined?'* an index of Disaster Resilience Indicators (DRIs) was developed with the aim of determining the base level of resilience present within communities and how this relates to the CI networks that underpin them. These indicators combine community and infrastructure resilience to provide STS decision-makers with information on how resilience is being impacted as new policies are introduced and investment in infrastructure is made over time. The advantage of empirical developments, such as the DRIs, are especially clear in relation to STS which may span multiple administrative regions, and help to identify the areas of vulnerability that require immediate attention. The data provided by the

DRI assessment is applicable for agents at all levels of the STS and so enhances agents' autonomy to improve the system resilience overall.

The DRIs are just one stage of the RMF which is detailed in Chapter 4. Further to RQ3. *'How can STS be managed to reduce physical, social and economic vulnerability to multiple hazards, increase capacity to tolerate and deal with change, and so achieve regional urban resilience?'* the RMF was designed to address the social, economic and physical aspects of resilience associated with STS. The RMF employs six stages to address this question and has an important application in educating STS practitioners, identifying core system assets, urban resilience analysis, vulnerability identification, developing adaptive resilience measurement and developing reconstruction strategies. These stages combine to address the multifaceted concept of STS resilience and STS-based management architecture, which are needed for shaping a transition towards resilience using insight based on analysis of a CI-based STS.

The design of the RMF in Chapter 4 was dependent on feedback from the case study and expert interviews. RQ4. *'Can a holistic resilience framework for the assessment of STS be developed and operationalised?'* is successfully addressed through the testing of the RMF, which was operationalised through a multi stage case study over two years. The STS was conceptualised in the form of the Dublin water management system which was tested through the case. Following the identification of vulnerabilities from the DRI analysis the STS adaptive capacity was enhanced using Internet of Things (IoT) flood sensors which were specifically developed for this task. While this technology was successful in enhancing the system resilience its introduction also raised issues around the how to effectively coordinate activity and the issue of underlying culture in the organisation. Interviews carried out with expert practitioners in relation to the case study highlighted the need for a quantitative assessment for resilience, which is flexible and applied in different urban contexts while also incorporating the social and economic realities of the environment under examination. STS boundaries to be inclusive of assets and impact factors outside of the traditional administrative boundaries of the systems component parts. This approach should be practitioner-orientated and highlight the need for users across all levels of the STS to proactively work together.

7.2.2 Impact of the Employment Based Research

Over the course of the employment based PhD the candidate worked in two different business contexts which supported the critical realism approach outlined in the methodology through undertaking the research within real world conditions. The employment based PhD also ensured that the RMF and associated resilience theory was tested in two different business contexts and demonstrated that the ideas worked in both settings. The two companies: Future Analytics Consulting (FAC), an urban planning and research consultancy, and VT-IoT, the Sigfox IoT network provider for Ireland were quite different in terms of their structure, management and research approaches. This context impacted on how the research was carried out by influencing the priorities for the research and - in the case of FAC - which areas were a priority for the preliminary literature review.

The research as strengthened by a multi-stakeholder approach. By being based in these companies the research was examined more rigorously as it was discussed and critiqued by a wider audience. The two years based in FAC was spent working on FP7 and H2020 EU research projects INDICATE and RESILENS. These projects gave the candidate experience on the design of research frameworks, informed the discussion around resilience development and ensured continued critical questioning both by the candidate and through discussion with leading resilience experts working on the project. The RESILENS project in particular informed the basis of the RMF and in particular the risk based DRIs. The RESILENS project also enabled the candidate to discuss and test the preliminary research questions and early draft of the RMF with international resilience experts.

Following this, a further year and a half was spent working in VT-IoT. Access to data on existing sensors deployments, locations, and data sets was made possible by relationships which were built up through the Employment Based Research. Specifically working with VT-IoT gave access to manufacturers whose knowledge was invaluable in understanding new technologies and potential solutions which could enhance resilience measurement. The developmental sensor types which facilitated the practical research were also uncovered due to contacts developed through the company networks.

Working with these companies allowed for the RMF to be designed and partially tested in a meaningful way in real world scenarios and with live feedback from industry experts and end users. As a SME using new technology the priority was for VT-IoT to be able to demonstrate the capability and value of their IoT communication network through the use of case studies. This led to the opportunity to design, test and validate new flood level sensors which were used as part of the RMF testing. This case study and the validation of the sensors and the RMF would not have been possible without the support of the company partner. The work in VT-IoT led to collaboration with the water management team in Dublin City Council. This collaboration involved the deployment and testing of the IoT sensor network.

7.3 Chapter Discussion

This thesis integrates urban resilience and an STS approach with traditional risk management theory (Chapter 2) into a conceptual RMF (Chapter 4) in order to maintain (and possibly improve) the functionality of STS during disaster events. The thesis also describes the context of the research problem and justification of the study of CI and specifically the water management system, and the research approach to addressing the research problem (Chapter 3). The RMF provides a robust foundation for the conceptualisation of resilience analysis and management, and was partially case tested on the Dublin Water Management STS (Chapter 5). Insights drawn from Chapters 2, 4, 5 and the findings in Chapter 6 are used to link concepts, answer the research questions and arrive at a number of conclusions (Chapter 7).

Following the expert interviews it is clear that there is clear disconnect between Ireland's emerging climate mitigation strategies and a sound theoretical basis for them. Through the case study of the RMF in Chapter 6, it is clear that the application of resilience theory to CI and the water management system in Dublin can better prepare them for disaster. This research contributes to closing this knowledge gap and provides evidence for the claim that the design of CI management in Ireland should be informed by the theory of urban resilience and STS based approaches (Chapter 2).

STS based governance architectures will be necessary if Ireland is to successfully meet the challenges of achieving resilience across each of the various CI types (Chapter 2).

In this thesis, we note that it would involve a multilevel, adaptive governance architecture, which combines notions of resilience *and* risk management in the context of climate impacts on Irish infrastructure, and in particular the water management system in Dublin. The research explores whether it is possible to achieve this by using an STS based conceptual framework and measurement tool to relate resilience to governance. To address this question, a case study was undertaken to realise aspects of the RMF and apply these to the water management system in Dublin (Chapter 6). The RMF is shown to provide a practical framework for relating the governance architecture to urban resilience in Dublin (Chapter 6).

In Chapter 1, it was proposed that in the place of CI management, building STS resilience should be used to improve the response of the water management system to flooding. The study of the water management system in Dublin and the subsequent analysis led to the following conclusions: Ireland's CI systems are identifiable as STS (Proposition 1). The related STS properties of economic, social and physical adaptability determine the possible resilience development trajectories of STS (Proposition 2). STS have an identity in relation to various geographic, socio economic, political, and institutional scales (Proposition 3). In terms of a complex systems hierarchy and socio-technical dynamics, the macro-regional level is a key focal level regarding resilience development and for the implementation of a multilevel management framework for achieving system resilience (Proposition 4). The case study of Dublin's water management system is an appropriate case in which to explore the concepts of STS resilience and the management framework in relation to CI resilience nationally (Proposition 5).

7.3.1 Literature review

The literature review considered categories directly pertinent to CI management; the main areas were resilience to natural and man-made hazards, resilient communities, resilience to climate change, and improving resilience of CI through the use of new technology. These categories overlap in several areas and authors suggested that these should be integrated where possible, and yet often continue to be presented as separate issues. Large-scale disaster events require high levels of adaptation of the urban fabric. Despite this, the literature review also exposed a trend of researchers associating

resilience with environmental and man-made threats, while failing to consider how other dangers associated with economic and social shifts in society may impact resilience (Section 2.4).

Much of the traditional risk analysis literature concentrates on the physical integrity of CI structures and does not account for the local communities that interact with the CI. The view of a city as a network of interdependent systems necessitates that guidance on resilience should be joined up more efficiently. Only by eliciting the interrelationships of climate change, adaptability of communities, and the flexibility of CI, can the resilience of the urban environment be improved. By merging these issues under the STS view, the impact of resilience measures can be monitored and maintained. The conceptualisation of the CI and the surrounding urban environment as an STS allows for important analogies and helpful conceptualisation of these systems, which can allow for benchmarking and resilience improvement. The STS concepts allow for a wider consideration of resilience and a complex systems approach as opposed to the siloed nature in which it has been analysed previously. Included in this is a view of the CI and the urban environment as a single system in which economic, physical, and social factors interact. The STS concepts are also useful in order to evaluate the resilience of an entire system rather than the component parts separately. An STS view also enables researchers to learn from this evaluation so as to improve the resilience through feedback loops.

7.3.2 Methodology

There is growing recognition that the pursuit of resilience requires new and more effective approaches to generating and applying science, technology and learning to solve complex, persistent problems of climate change. This thesis adopted an STS approach to resilience research. It addressed socio–technical relations through a framework based on urban management and socio-technical science (Chapter 4). Together, socio-technical and resilience science provided a philosophical and theoretical foundation: a logical structure for the integration of complementary components of different theories relevant to STS research. Overall, the STS approach to resilience research provided a sound basis for guiding this research.

The critical realism perspective adopted provides not only a basis for justification for case study research of this nature but also supports the use of a limited number of expert interviews. Critical realism fits well with this research as STS are so large that no one person can comprehend the extent of the entire system and all of the inner workings both physical or social. It must be noted as well that observations and conclusions based in a critical realist perspective cannot be proven to be right, only that there is acceptance from stakeholders of the findings of the research. In this case the experts and the researcher either explicitly agreed how the world (or the system) operates or at the very least they behaved as if it was.

Investigating complex socio–technical relations and interactions requires a conceptual framework to help organise and integrate different types of knowledge and reconcile different theoretical and analytical perspectives. However, integration of social and technical knowledge is impeded by the lack of coherent, integrated and interdisciplinary frameworks to guide the conceptualisation of research concerning STS. This research required a conceptual framework to: (1) accommodate concepts derived from different disciplines and perspectives; (2) allow relevant concepts and their (assumed) relationships to be identified, gathered and organised; and (3) provide a general, abstract explanation of key concepts and their relationships, which in turn served as the theoretical basis and justification for the conceptualisation and analysis of the water management system in Dublin (Chapters 4, 5 and 6 respectively).

7.3.3 RMF Design

Taking the long-term changing climate patterns into account, conventional urban planning and management often relies on risk analysis, which quickly become outdated. These include risk projections, which may be labour intensive and are carried out over an extended time period. Despite the known lack of accurate models, urban development plans continue to be formulated based on these outdated risk methods. The review of the literature uncovered a number of conceptual approaches to plan for uncertainty in the urban environment (Section 2.6). This over-simplification of reality may be useful to get a snapshot of the state of the urban environment at a particular

time, but this data must be regularly updated if it is to inform ongoing decision making. This outdated approach is not suitable for the current reality of rapid climate change where the natural, societal and economic condition of urban systems are volatile and dynamic.

Scenario-specific tools are currently used in many sectors to explore system management coping mechanisms, although a tool that considers all levels of the STS - such as the RMF - is much needed. An alternative approach was envisaged adopting resilience theory and STS concepts, which could address the continually evolving conditions seen in today's climate conditions. It can be concluded that as resilience is about responding effectively to uncertainty, a flexible framework and tools are necessary for such a purpose. An interactive tool was developed that can be used to examine a diverse range of STS types, give a baseline resilience analysis, and be used to determine potential strategies and tools to improve their resilience over time. The method was tested on the water management system in Dublin. By focusing on the forces that can determine how an STS can respond to any disaster type and by developing plausible directions of resilience measurement and management the RMF can address these concerns. The innovative use of new tools to monitor and improve resilience over time were also developed. They enable a more regular scanning of the risk horizon in a systemic fashion, this analysis can capture societal and natural dynamics in a way that can be updated more frequently and is not dependant on once off analysis.

The post climate change era is upon us and already the effects on CI such as transport, water and energy networks are being felt. Policy makers and CI managers are beginning to come to terms with a greater variability in climate. Many developments at local, regional and national level, from housing to major infrastructure projects are still being constructed on the assumption that future climate will be similar to that of the present. The DRIs will contribute by making new developments more climate proof, there will be an additional level of complexity, but there will also be a greater level of STS resilience. As research on STS resilience is expanded these DRIs will provide researchers with an initial method to measure baseline resilience, however, DRIs are not exhaustive and it is expected that additions and alterations may be necessary to reflect the particular needs of different contexts.

Measurement indexes, such as the DRIs presented here, advance our understanding of resilience and provide policy makers and CI managers with an awareness of resilience's multidimensional nature. The index equips them with the tools necessary to quickly visualise any vulnerability in their community. These vulnerabilities can then be extricated to provide metrics that are easily understood and applicable to the decision-making process. The DRIs will provide a useful way to examining not only the composite score of a particular community, but also allows for comparisons between communities to be made. While regional authorities may be more interested in the overall patterns and look for intervention strategies that improve the entire region, local policy makers, including county and town councillors, might be more interested in intervention opportunities at the county scale. It was noted in the course of this research and RMF development that many frameworks designed to embed resilience in urban systems result in a baseline that remains static through the life of the project, which may continue years after the initial analysis is carried out. As the STS develops, the baseline measure should be updated regularly. The RMF aims to address these shifting dynamics: The DRI is designed so that each individual indicator can be updated as new data becomes available and easily inserted to update the overall resilience score. As the resilience score shifts, different decision-makers must adapt accordingly, as different managerial approaches and tools may be required.

7.3.4 Case Study

The analysis subject of the case study was on the water management system in Dublin. The holistic nature of the scenario-based method, however, allowed the exploration of socio-economic, policy, and behavioural factors directly and indirectly connected to water management and flood management strategies. The analysis led to three main conclusions on the essence of the resilience analysis and of the approach necessary to designing resilient cities.

Resulting from the initial research and data gathering for the DRIs and baseline resilience measurement, a final resilience score was arrived at. The resilience score does not give an unequivocal answer but rather can suggest areas where the resilience of the STS may be improved. Secondly, the quantitative DRI score alone could was not

enough to inform decision making and relied on the secondary qualitative input of the expert panel to deliver a sound pathway to improving the resilience of the STS. Finally, the resilience analysis is context sensitive as it focuses on flood conditions as the primary threat to the water management system. Although many other STS in Ireland will face the same threats, it is unlikely that flooding will be the primary threat in each case. The resilience analysis focuses on conditions to maintain the functionality of the STS, which are dependent on the evolution of the local environment and its response to unique pressures and circumstances. These three features are inherent to urban resilience and should be used as the foundation for any resilience management paradigm. Further decisions made towards improving urban resilience must be criticised and probed in a repeated systematic fashion to ensure the consequences of design choices continue to deliver their designed impact.

On the basis of the case study, advantages and shortfalls of the resilience analysis were discussed and, more importantly, its characteristics compared with those of current risk assessment methods. Limits of the resilience analysis include: the reliance on the still necessary qualitative opinion of decision makers, which can impact the reliability and repeatability of the evaluation; and the multiple possible resilience improvement tools, as opposed to an unequivocal outcome resulting from the DRI and interview stages. These limits however, are also the RMF's strengths since they allow a high level of flexibility in determining design strategies, and this was one of the features that the expert panel believe is of benefit when dealing with a such broad systems.

The case study relied on expert opinion as a primary source of information during the study of the water management system. This entailed using three methods: Firstly, a procedure for identifying and selecting suitable individuals with appropriate expertise. Secondly, designing the interview questions in order to elicit the data for collection. Thirdly, adopting the KNRW as an analytical strategy and method of data analysis. (See Chapter 5.) The expert panel method resulted in 13 participants in the study.

One of the main conclusions coming from this study is that greater levels of communication between the management bodies is imperative. This is in line with the multi-level governance literature and in particular with local and national level organisations operating within the same system. The large number of management

bodies responsible for flooding across the water management spectrum, including the Office of Public Works (OPW), Irish Water, Dublin City Council (DCC) and Waterways Ireland, creates a difficulty with regards coordination. The responses for large scale planning is also negated by subdividing the authorities into smaller subdivisions. Following the case study the need for a county or region wide flood coordination authority to review all aspects of water management across the area of the STS is clear.

Further to the interview analysis, the number of organisations and the different levels within and between them results in a dispersion of authority. The number of jurisdictions with responsibility for various parts of the water management system also means that coordination and rapid response in the time of flooding is hampered. A solution to this would be to have a singular, region wide, flood response team which could coordinate and prepare the various management bodies for a disaster event.

7.4 Limitations

7.4.1 Multi-disciplinary Research

The main challenge experienced during this research was the element of interdisciplinary nature necessitated when researching STS. This required the interpretation and application of methodologies from across different disciplines including management, engineering, and the social sciences. Of the challenges necessitated by the exploration and development of new frameworks, the development of coherent methodological approach was of primary concern. This led to the establishment of connections between disparate methods of investigation including the qualitative expert interviews and the quantitative DRI and flood sensor analysis. Furthermore, the search for information on the state of resilience through the expert interviews required interpretation as to the meaning of language used by the experts across different domains, where a shared definition first had to be established. The selection of content for the interview questions, and the expert panel selection required more extensive background study and research, than if the research area was being carried out on a single disciplinary research area. Ultimately, the work to ensure the harmonisation of aspects from diverse methodologies required significant time allocated to research, discussion with supervisors and experts before reviewing the

approach and, in some cases, repeating stems of the RMF development and case. This process ensured the consistency of the research progress and resulted in a formative process. The multidisciplinary approach led to a deeper understanding of the complexity of STS and opened a dialogue between experts from different disciplines. This dialogue widened perspectives and new avenues for further research.

7.4.2 DRIs

Several criticisms of the quantitative indicator approach have been noted by researchers, including subjectivity regarding variable selection and weighting, lack of availability of certain variables, problems with aggregation to different scales, and difficulties validating the results (Luers et al., 2003; de León and Carlos, 2006). These criticisms were mitigated through rigorous literature review prior to selection, a further review of the indicators by the expert panel and, although the indicators may be weighted if particular system aspects require scrutiny, then weightings may be applied. The usefulness of quantitative indicators for reducing complexity, measuring progress, mapping, and setting priorities makes them an important tool for decision makers.

The DRIs aim to be a useful quantitative measures of community resilience and are unique in the attempt to combine CI resilience with community resilience to this degree, but they are not without limitation. The reliance on national census data which although only recently amended in 2015 will only be updated every four years. In some cases, census data may not be available at low levels, and therefore may not be comparable across communities. We will work with local authorities and CI operators to employ expert knowledge where supporting data is lacking.

The suite of indicators which influenced the development of the DRIs were based on indicators put forward in the literature across a range of disciplines. The DRIs may be restricted by the availability of existing indicators as inspiration as community resilience research is still in its infancy.

7.4.3 Case Study

Case studies are often used for large complex problems such as climate change, sustainability or resilience research where there is a need for qualitative, inductive

research to better understand the issue. This research can then inform subsequent quantitative, deductive research and potentially generalisable results. Causal inferences cannot be made from case studies as alternative explanations for outcomes may exist. There is also an issue around the generality of case study research as they only involve a specific subject, in this case the water infrastructure in Dublin. The behaviour of this system may or may not reflect behaviours of water systems or indeed other STS in different cities within Ireland or in the wider EU generally. This case study may be suggestive of what results may be found in similar STS but additional research is needed to verify whether generalisations may be accurately applied elsewhere.

The suggestion that resilience could be improved through a regional oversight body with responsibility for coordinating the water management teams in theory would open the communication between the jurisdictions facilitating coordination while gaining the scalar benefits of multi-level governance. This would allow the OPW, DCC and IW to focus on their core competencies while ensuring an oversight function which could be applied during flooding or other crisis events. These ideas around alternative governance measures for the system cannot be validated without an extensive cost benefit analysis of alternative governance types. Good comparative data on alternative governance structures for STS and their benefits are needed for further analysis which is beyond the scope of this research.

7.4.4 Employment Based Research

While the employment based environment was generally highly beneficial for the research there were certain elements which created additional work and in some areas slowed the progress of the research. While working with private companies was hugely rewarding with regards to access to experts, involvement on practical projects and for practical testing opportunities there were challenges where company objectives did not always align with the research. In many cases client need and deliverables had to be prioritised over the long term research project objectives. The reporting and multiple stakeholders also meant that there was a high level of bureaucracy which had to be managed which was time consuming.

The major challenge for the research in working with private industry was the conflict of carrying out independent research as an employee of a company where any output is viewed as the property of the company. Strict boundaries had to be drawn to ensure that the research carried out for the PhD was solely the work of the candidate which was in conflict of the work culture where management would oversee and direct employees on exactly what they should be working on.

7.5 Contributions

The main contributions to the resilience management field are (i) theoretical, (ii) empirical and (iii) practical contributions.

7.5.1 Theoretical Contribution

The main theoretical contribution is the new resilience management framework (RMF). The development, testing and validation of the RMF demonstrates a clear case for moving from an engineering resilience focus on Critical Infrastructure to Socio-Technical Systems (see pgs.148, 149, 155). The RMF was developed (p.82) in response to the traditional ‘machine view’ of the world as we now know that infrastructure systems are operated by multiple autonomous actors. The RMF as proposed also demonstrates the benefits of moving from a ‘risk-based’ resilience approach to a ‘stakeholder-based’ resilience approach (p. 137).

By carrying out a review of the range of theoretical models that have been developed for the evaluation of the resilience of CI it was possible to evaluate how appropriate these models are to address the research questions. The approach led to the development of an objective evaluation of their suitability to CI systems. Following the evaluation, the view of CI as stand-alone engineering systems was replaced with an STS perspective which more closely aligned with the nature and operation of CI systems. From an STS viewpoint the CI itself is viewed as a part of the wider urban environment to include social and economic factors. Using this combined STS and resilience paradigm the theoretical contribution of the proposed RMF and specifically the DRI assessment framework was developed. The DRIs address the economic, social and physical aspects of the STS which is a further contribution to the literature and theories on resilience management.

7.5.2 Empirical Contribution

Secondly the empirical contributions to knowledge include demonstrating how the resilience of STS may be monitored. Through the development and caseing of the RMF a novel framework of STS resilience management has been demonstrated, this is the first of its kind. This research provides a method for identifying areas of low resilience due, not only to infrastructure issues, but also economic and social issues. Decision makers can now prioritize where to allocate scarce resources to improve the overall resilience in these areas.

A large body of research has been carried out on the economic impacts of disaster events on systems but some commentators question the dominant emphasis on large-scale urban environments and aggregated macro-economic approaches, and the corresponding lack of empirical research on CIs themselves. This literature points to a greater need to focus on case studies and analytical narrative. The use of a comparative case-study methodology in this research provides insights into the processes and participants involved in resilience measurement and management.

7.5.3 Practical Contribution

With regards to the practical contribution the output of the RMF in the form of the DRI tool and the effective use of IoT sensors in practice are valuable contributions with real world application. Furthermore the interdependencies between overlapping STS remains under-developed. The decision makers working at each level of the STS must all come together in order to improve the resilience of the STS. The proposed modification of existing risk and resilience models (detailed in Chapter 3) to allow for the inclusion of additional fit-for-purpose analysis areas, is a novel contribution to this field. These areas include the analysis not just on a geographic or administrative level but a combined boundary that includes as many elements of the system as possible. The use of the DRI analysis can cross the bounds of different STS levels providing agents at all levels with the information to improve the resilience of their own area (i.e. the inclusion of a pathway through which resilience can be meaningfully explored at varying spatial levels).

In addition, the Expert Interviews highlighted the issue of deciding the system boundary based only on administrative or geographical features. For future projects this should be decided with input from all STS stakeholders as a ‘Stage 0’ of the RMF.

7.6 Further Research

The ideas presented in this thesis are intended to be useful to policy makers, academic practitioners and infrastructure managers who are concerned with achieving resilience in their cities. Although in its infancy, the RMF approach to resilience has the potential to guide the design and development of governance architecture for CI systems in Ireland and other European countries. The application of urban resilience theory to CI systems and the communities they support offers a framework for linking concepts and guiding understanding of socio-technical relations. The general design guidelines for a resilience based multilevel adaptive architecture for STS governance as presented in this theses provide further information for debate and a basis for future research. Much work remains to be done in order to strengthen the argument for the adoption of resilience theories in the management frameworks of Critical Infrastructure across Europe. A number of academic papers are planned to develop these ideas and bring them to a wider audience. The development of these papers will require a number of further steps:

- The DRIs will form the basis of a resilience score which will provide spatial assessment as well as an empirical ranking of the most and least resilient communities across Ireland. In order to be a succinct resource for decision makers further detail around the stages of the RMF need to be developed. Specifically the reconstruction stage may require a an alternative case study case where a disaster has occurred to test.
- The deployment of a wider sensor network to provide sufficient data for large scale data analysis and to develop information flows to properly advise decision makers.
- Additional case studies, which can act as a comparison for the Dublin water management STS, are needed especially across different cases to show real world comparability of resilience level between STS. Additional case studies will contribute to the validation of the RMF approach.

- The application of the RMF to an alternative urban environment with a different geography and risk profile. The RMF can be further refined through additional research and input from wider expert opinion through further individual interviews or workshops and table-top exercises.

As the urban resilience field continues to expand there are a number of questions which remain to be answered. Too often resilience frameworks are disconnected from the reality of data available in cities. This needs to be addressed from many angles including a socio technical approach to resilience governance. Secondly as it grows in popularity urban resilience is becoming further disconnected from its philosophical (ontological and epistemological) foundations. Work is needed to strengthen these foundations and to ensure a more clear understanding of urban resilience among practitioners across the research fields it may be applied to. Following the case study it is clear that regional level management is missing from the governance structure in Ireland.

This research is predominantly conceptual in its approach although there are a number of practical findings which have also been demonstrated. I believe the findings provide a sound basis for future research into social–technical resilience in Ireland and in a wider European context. The application of the RMF has demonstrated the potential of urban resilience to address the impacts associated with disaster weather events affecting European cities.

This research has attempted to show how resilience can be measured so that steps can be taken to reduce the impact of disaster events on our cities. I will conclude this thesis with one very important question: can we achieve resilience for our cities which is both sustainable and inclusive for all communities therein?

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APPENDICES

Appendix A Critical Asset Indicators

	Indicator Title	Description	Scale (Score)
1	Coverage Area	Percentage of total CI geographic service area as impacted by the individual asset	• High (3): 61-100% • Medium (2): 21-60% • Low (1): 1-20% • None (0): 0%
2	Population Coverage	Percentage of total CI client base impacted by the asset	• High (3): 71-100% • Medium (2): 41-70% • Low (1): 1-40% • None (0): 0%
3	Societal Impact	Potential injuries and casualties with the loss or failure of the asset	• High (3): Any deaths • Medium (2): 11-25 people effected • Low (1): 1-10 people effected • None (0): No injuries
4	Natural Habitats Impacted	Environmental damage: Including but not limited to; soil erosion, damaged or destroyed coastal vegetation and contaminated inland water bodies, pollution of water reserves, and the increased level of wastewater from damaged infrastructure which may pose serious public health concerns.	• High (3): Permanent destruction of surrounding natural habitats • Medium (2): Long term impact of 5+ years, resulting in the death or migration of local species • Low (1): Minor pollution of water/soil which will not require human intervention to solve • None (0): No impact on natural habitats
5	Impact time	Time between disaster and effect on stakeholders	• High (3): Over 12 hours • Medium (2): Under 12 hours • Low (1): Under 1 hour • None (0): No time between event and effect
6	Historical Value	Societal significance of the asset	• High (3): Landmark asset with high visibility and public interest • Medium (2): Historically significant but with little public interest • Low (1): Local cultural importance with little public interest • None (0): No public awareness or interest in the asset

7	Value of the asset	Monetary value of asset purchase	• High (3): < €1,000,000 + • Medium (2): < €700,000 • Low (1): < €400,000 • None (0): 0
8	Asset repair	Monetary value of asset repair	• High (3): < €1,000,000 + • Medium (2): < €700,000 • Low (1): < €400,000 • None (0): 0
9	Community Contribution	% contribution of the identified asset functioning on the local economy	• High (3): < 3%+ • Medium (2): < 2% • Low (1): < 1% • None (0): 0%
10	Billing	Asset payment by the provider	• High (3): 71-100% Ownership (4) • Medium (2): 41-70% Ownership • Low (1): 1-40% Ownership • None (0): 0% Not owned by the provider
11	Strong integration with other assets	Strong integration between the local economy and wider economic systems.	• High (3): 4+ asset links • Medium (2): 2 - 3 asset links • Low (1): Linear link to single asset • None (0): Standalone asset
12	Fiscal Contribution	Contribution to the total CI value	• High (3): 15%+ • Medium (2): 6-15% • Low (1): 1-5% • None (0): 0%
13	Percentage Output	The relevance of the identified asset with regards to the CI core asset provision	• High (3): 15%+ • Medium (2): 6-15% • Low (1): 1-5% • None (0): 0%
14	Redundancy I	Availability of a redundant asset	• Yes (3) • No (0)
15	Redundancy II	Retained spare capacity; The average operating level as a percentage of the maximum possible	• High (3): 80% + • Medium (2): 60-79% • Low (1): 1-59% • None (0): 0%
16	Flexible infrastructure services	Can asset services be repurposed for alternative uses? And how important is that alternative use?	• Yes (3) • No (0)

17	Strong integration with other assets	Linkages with other assets in terms of the inflows and outflows, showing the importance for the CI system network	• High (3): 4+ asset links • Medium (2): 2 - 3 asset links • Low (1): Linear link to single asset • None (0): Stand-alone asset
18	Asset Activation	An asset that is used by a business in its daily or routine operation	• High (3): Continuously / Daily • Medium (2): Weekly • Low (1): Monthly • None (0): -

Indicator Type: Social Resilience
Soc01: Educational Equity Description: this indicator measures the educational attainment of the local populous Metric(s): Ratio of the percentage population with 3rd level education attainment in the area Original reference(s) for indicator: Norris et al., 2008 Impact on resilience: Positive impact benefitting the STS Data availability: This data is generally available in European Cities Cilot Study Data Source: Pobal deprivation indices; https://maps.pobal.ie/WebApps/DeprivationIndices/index.html Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format. Comment: NA
Soc02: Health Description: this indicator measures the health of the populous Metric(s): Percentage population with good health Original reference(s) for indicator: Heinz Centre, 2002 Impact on resilience: Positive impact benefitting the STS Data availability: This data is generally available in European Cities Case Study Data Source: Central Statistics Office, Census data; http://census.cso.ie/p9map42/ Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format. Comment: NA
Soc03: Population Coverage Description: this indicator measures the number of citizens who are impacted by the functionality of the STS Metric(s): Population high in the area Original reference(s) for indicator: Singh Peterson et al., 2014 Impact on resilience: Negative impact affecting the local community

Data availability: This data is generally available Case Study Data Source: Pobal deprivation indices; https://maps.pobal.ie/WebApps/DeprivationIndices/index.html Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format. Comment: NA
Soc04: Local Affluence and Deprivation Description: this indicator measures the wealth gap in the local community Metric(s): Haase Pratske Score Original reference(s) for indicator: Norris et al., 2008 Impact on resilience: Positive impact benefitting the local community Data availability: This data is generally available Case Study Data Source: Pobal deprivation indices; https://maps.pobal.ie/WebApps/DeprivationIndices/index.html Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format. Comment: NA
Soc05: Dependency Description: The more the dependent age groups in a population, the more time and resources are needed to aid or evacuate during a disaster event Metric(s): Percentage population over 65 and under 15 Original reference(s) for indicator: Qasim et al., 2016 Impact on resilience: Negative impact on the local community Data availability: This data is generally available Case Study Data Source: Central Statistics Office, Census data, available from http://census.cso.ie/p3map24/ Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format. Comment: NA

Soc06: Municipal Services

Description: this indicator measures the availability of necessary services to the community

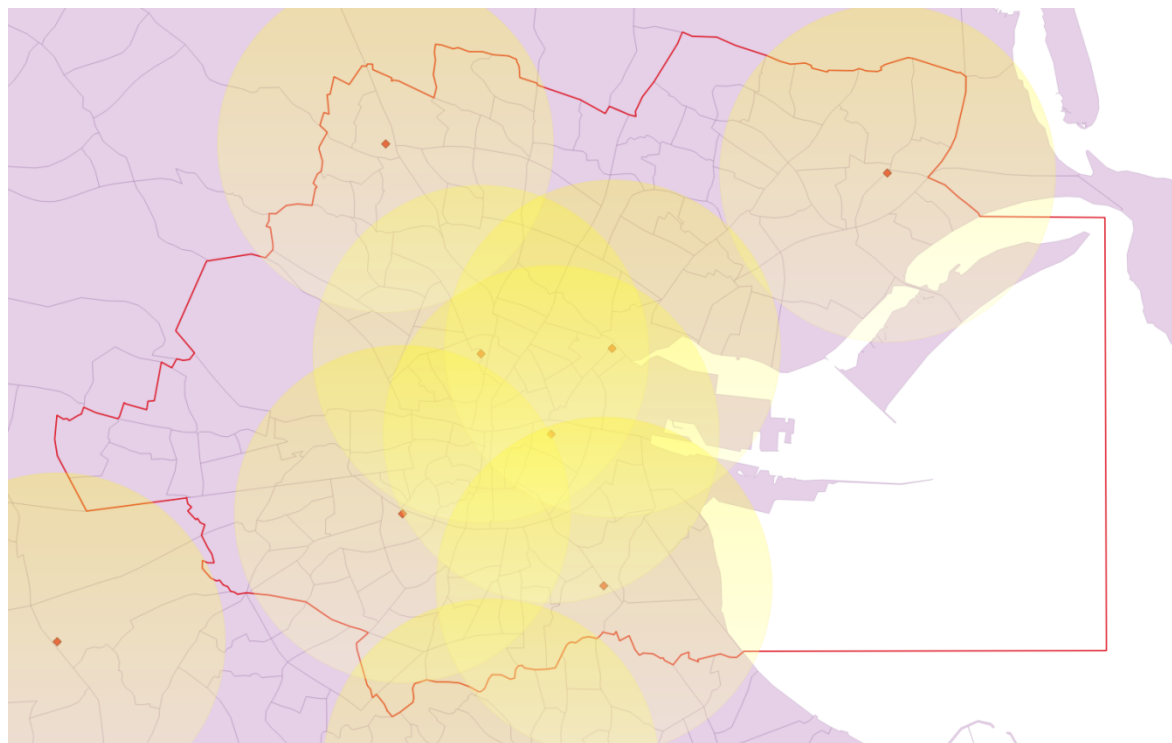
Metric(s): Proximity to prevalent municipal services (fire, hospitals, police stations)

Original reference(s) for indicator: Sylves 2007; Cutter et al. 2010

Impact on resilience: Positive impact benefitting the local community

Data availability: This data is generally available

Case Study Data Source: GIS shape file of station locations and service area



GIS shape file displaying fire stations and their service areas

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: A study by the National Oversight and Audit Commission, a body set up to provide independent scrutiny of the performance of local authorities, found the proportion of fires reached within 10 minutes had increased in 18 council areas in 2018. In contrast, the proportion of fires where it took over 20 minutes for the first fire brigade to attend the scene had risen in 13 fire authorities. Fire crews in urban areas have the fastest response times with Dublin City fire brigade units reaching almost 78% of all reported fire scenes within 10 minutes.

Soc07: Voter Participation

Description: this indicator measures the public's engagement with the political process Metric(s): The voter participation in the as a percentage of total population Original reference(s) for indicator: Singh-Peterson et al., 2014 Impact on resilience: Positive impact benefitting the local community Data availability: This data is generally available Case Study Data Source: Turnout figures for the 2016 general election in Ireland, data based on analysis of turnout figures by Dr Adrian Kavanagh Maynooth University Department of Geography April 2016. Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format. Comment: NA
Soc08: Cultural Diversity Description: this indicator measures the range of different nationalities within the populous Metric(s): International population % Original reference(s) for indicator: Magis, 2010 Impact on resilience: Negative impact on the local community Data availability: This data is generally available Case Study Data Source: Central Statistics Office, Census data, available from http://census.cso.ie/p2map26/ Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format. Comment: NA
Indicator Type: Economic Resilience
Econ09: Owner Occupied Housing Description: this indicator measures the number of owner-occupied houses in a community Metric(s): Houses occupied by their owners Original reference(s) for indicator: Ostadtaghizadeh, et al., 2015. Impact on resilience: Positive impact benefitting the local community Data availability: This data is generally available Case Study Data Source: Central Statistics Office, Census data, available from http://census.cso.ie/p1map31/

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Econ10: Female Employment

Description: this indicator measures the percentage of the female population in full-time employment

Metric(s): Percent working age population (F)

Original reference(s) for indicator: Morrow, 2008

Impact on resilience: Negative impact on the local community

Data availability: This data is generally available

Case Study Data Source: Pobal deprivation indices;

<https://maps.pobal.ie/WebApps/DeprivationIndices/index.html>

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Econ11: Male Employment

Description: this indicator measures the percentage of the male population in full-time employment

Metric(s): Percent working age population (M)

Original reference(s) for indicator: Morrow, 2008

Impact on resilience: Negative impact on the local community

Data availability: This data is generally available

Case Study Data Source: Pobal deprivation indices;

<https://maps.pobal.ie/WebApps/DeprivationIndices/index.html>

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Econ12: Land Value

Description: this indicator measures the value of land in a community

Metric(s): Monetary value of system development

Original reference(s) for indicator: Kelman, 2013

Impact on resilience: Positive impact benefitting the local community

Data availability: This data is generally available

Case Study Data Source: Revenue, local property tax, <https://lpt.revenue.ie/lpt-web/valuation-guide/index.htm>

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Econ13: Interdependencies with other urban systems

Description: Linkages with other assets in terms of the inflows and outflows, showing the importance for the CI network

Metric(s): Linkages with other assets in terms of the inflows and outflows

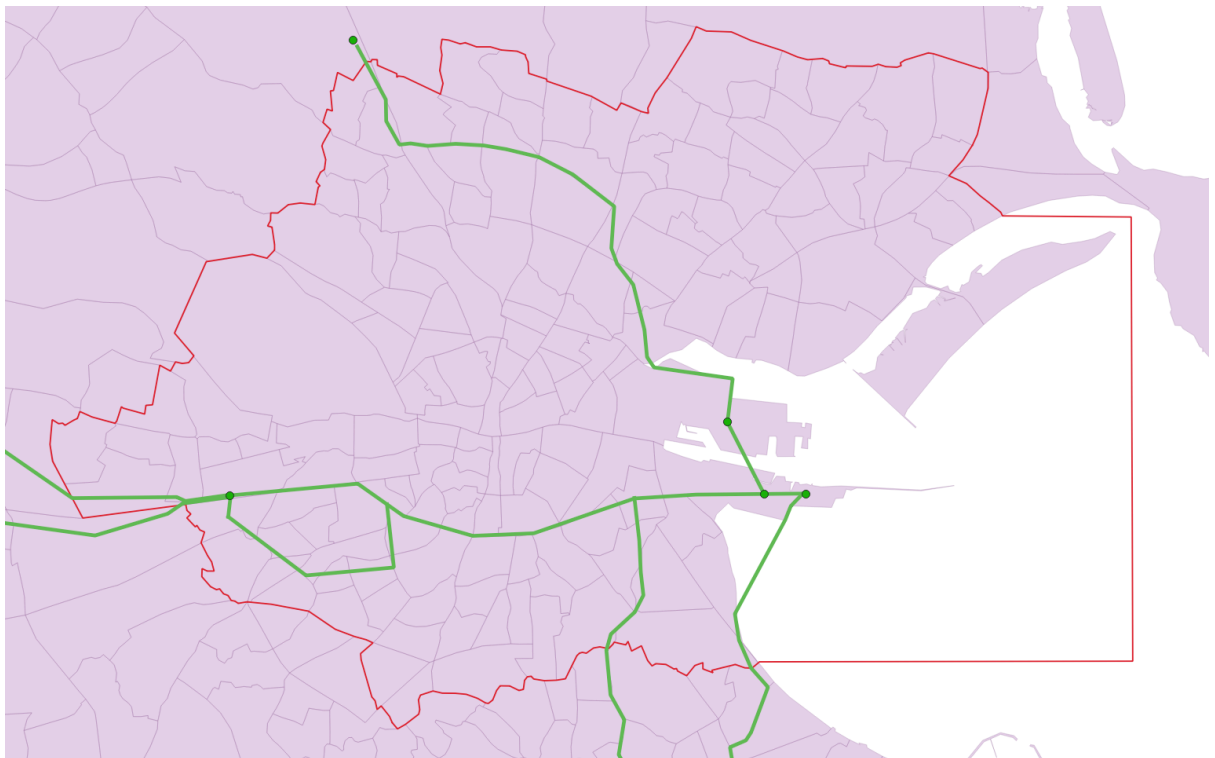
Original reference(s) for indicator: Tyler and Moench, 2012

Impact on resilience: Positive impact benefitting the local community

Data availability: This data is generally available

Case Study Data Source: Eirgrid Group transmission map

<http://smartgriddashboard.eirgrid.com/#all/transmission-map>



GIS shape file displaying primary energy supply stations and cables (200kw)

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Econ14: Housing Stock

Description: Housing available in the community

Metric(s): Housing available in the community

Original reference(s) for indicator: Ainuddin and Routray, 2012.

Impact on resilience: Positive impact benefitting the local community

Data availability: This data is generally available

Case Study Data Source: Central Statistics Office, Census data, available from

<https://statbank.cso.ie/px/pxeirestat/Statire/SelectVarVal/Define.asp?maintable=E1068&PLanguage=0>

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Econ15: Derelict Buildings

Description: this indicator measures the number of derelict buildings in the community

Metric(s): Derelict buildings in the community

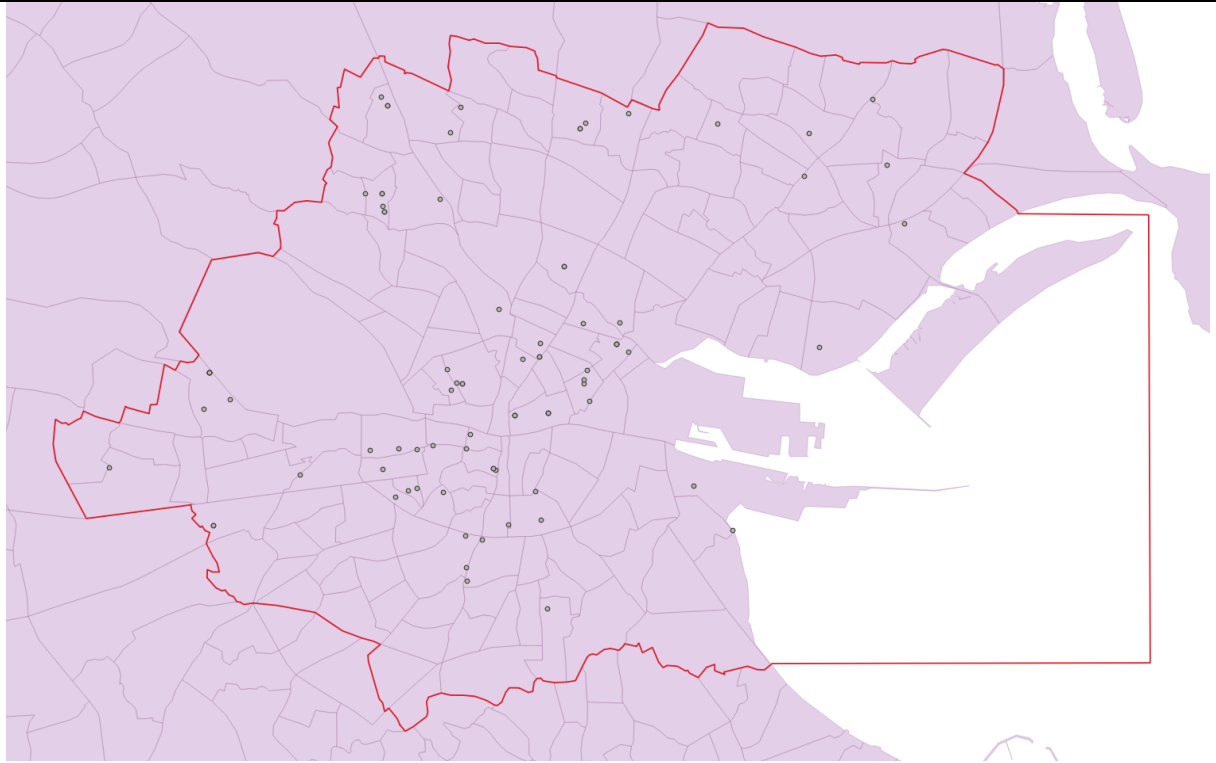
Original reference(s) for indicator: Crowe et al., 2015

Impact on resilience: Negative impact on the local community

Data availability: This data is generally available

Case Study Data Source: Dublin City Council, Derelict Sites Register

<http://www.dublincity.ie/main-menu-services-planning/derelict-sites>



GIS shape file displaying the location of derelict buildings

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Econ16: Vacant Buildings

Description: this indicator measures the number of vacant buildings in the community

Metric(s): Number of vacant buildings in the community

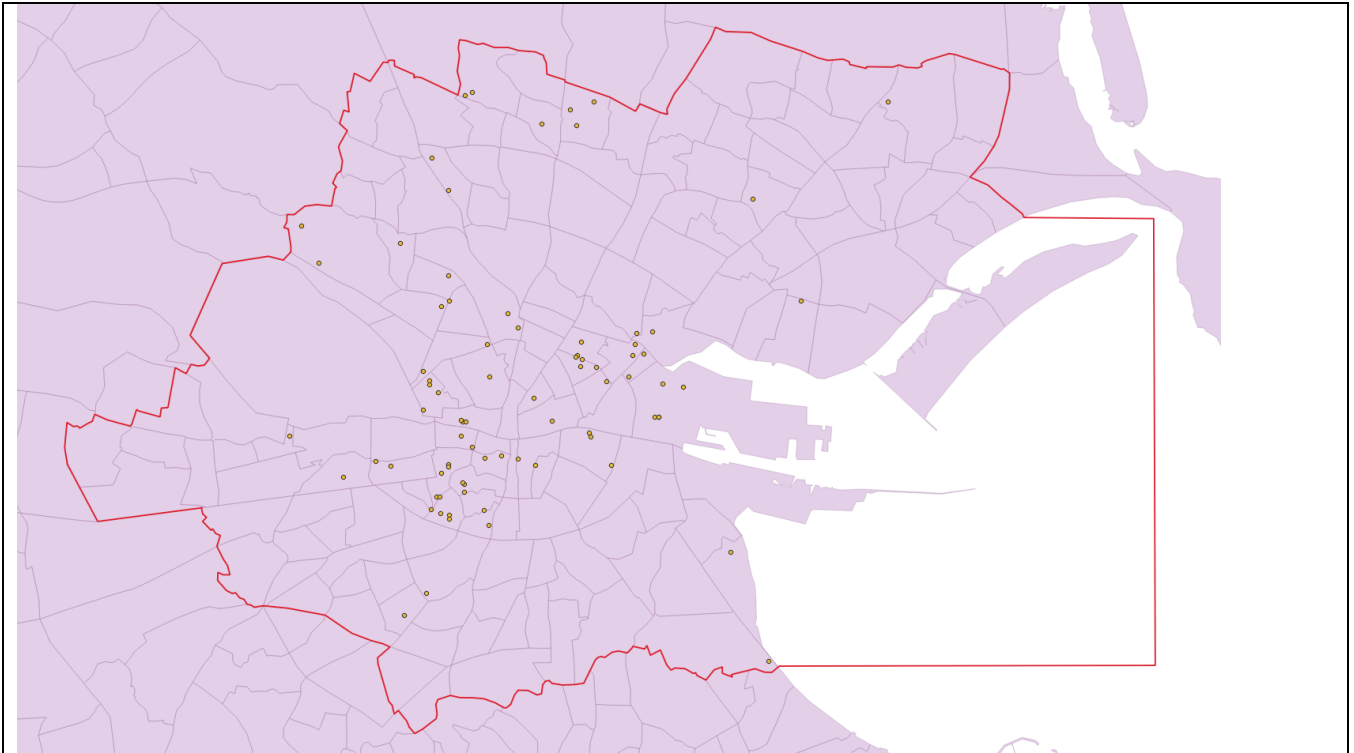
Original reference(s) for indicator: Crowe et al., 2015

Impact on resilience: Negative impact on the local community

Data availability: This data is generally available

Case Study Data Source: Dublin City Council, Vacant Sites Register

<https://www.dublincity.ie/sites/default/files/content/Planning/Documents/VacantSites.pdf>



GIS shape file displaying the location of vacant buildings

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Indicator Type: Critical Infrastructure Resilience

Infr17: Low risk areas

Description: this indicator measures the local low risk of primary disaster in the area

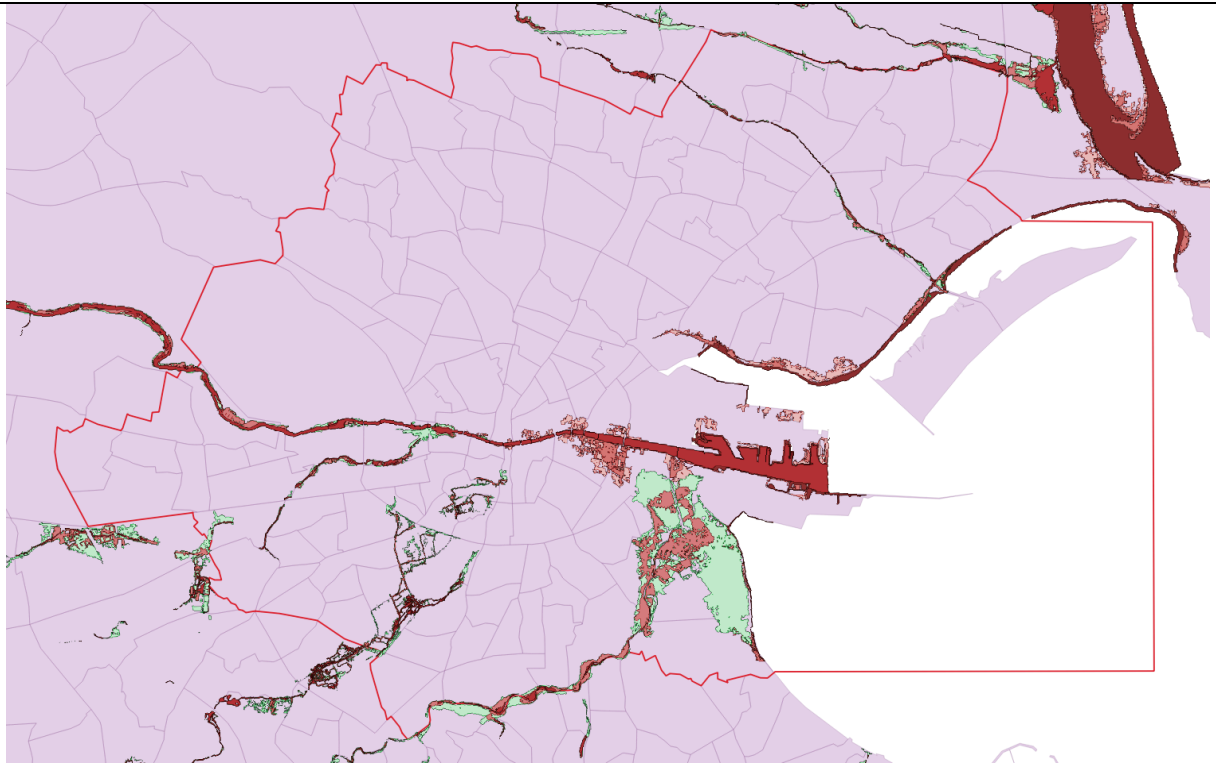
Metric(s): Local low risk of primary disaster in the area

Original reference(s) for indicator: United Nations, 2004

Impact on resilience: Negative impact on the local community

Data availability: This data is generally available

Case Study Data Source: Commissioners of Public Works, CFRAM, Flood Maps, available from <https://www.floodinfo.ie/map/floodmaps/>



GIS shape file displaying present low risk coastal and fluvial flooding

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: Risk analysis of the Poddle river is currently being carried out by the OPW and once complete this may influence the risk profile of the areas affected by the river.

Infr18: Medium risk areas

Description: this indicator measures the local medium risk of primary disaster in the area

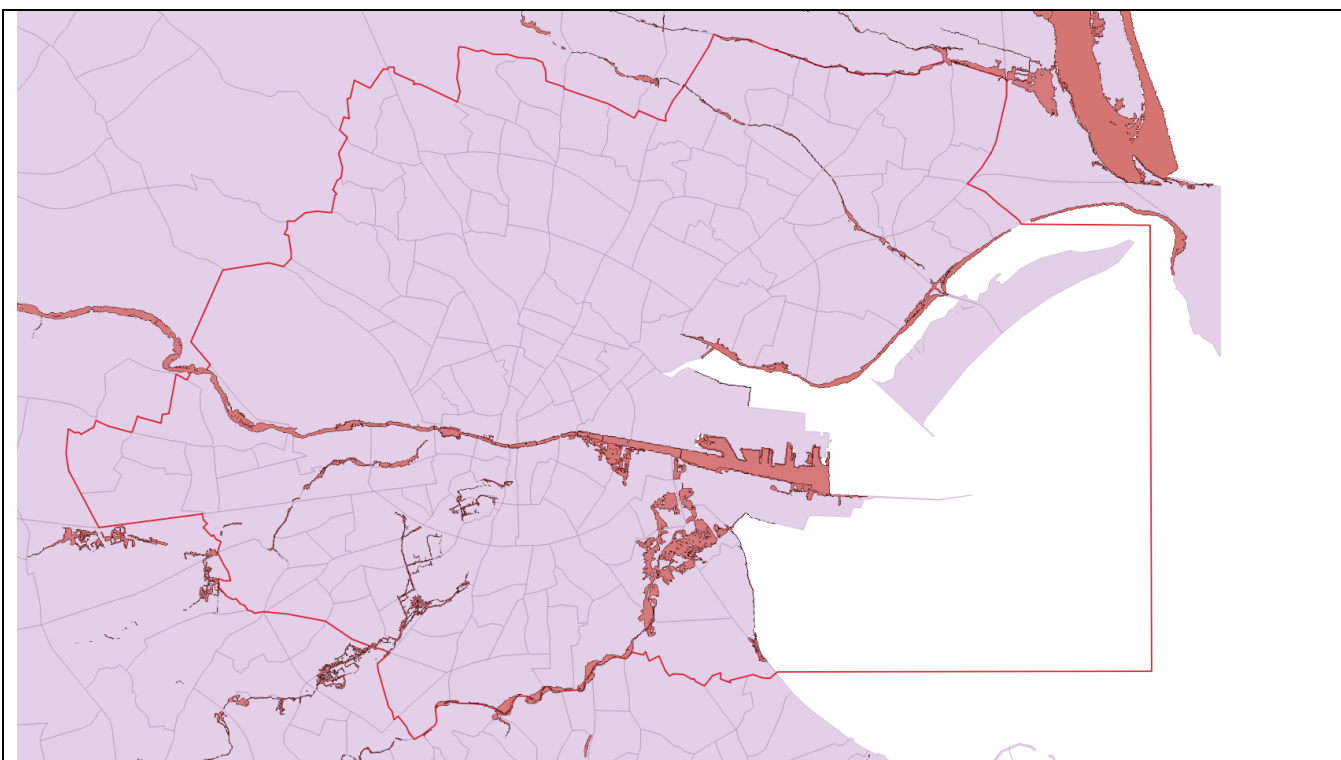
Metric(s): Local medium risk of primary disaster in the area

Original reference(s) for indicator: United Nations, 2004

Impact on resilience: Negative impact on the local community

Data availability: This data is generally available

Case Study Data Source: Commissioners of Public Works, CFRAM, Flood Maps, available from <https://www.floodinfo.ie/map/floodmaps/>



GIS shape file displaying present low risk coastal and fluvial flooding

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: Risk analysis of the Poddle river is currently being carried out by the OPW and once complete this may influence the risk profile of the areas affected by the river.

Infr19: High risk areas

Description: this indicator measures the local high risk of primary disaster in the area

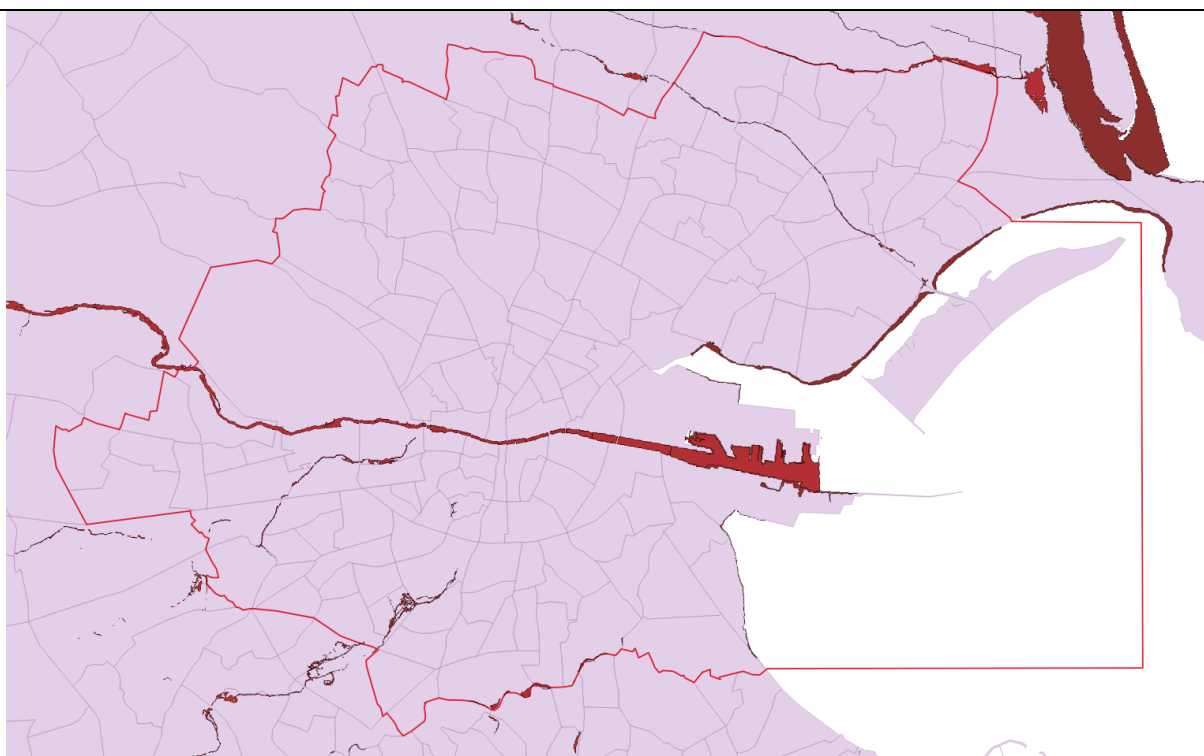
Metric(s): Local high risk of primary disaster in the area

Original reference(s) for indicator: United Nations, 2004

Impact on resilience: Negative impact on the local community

Data availability: This data is generally available

Case Study Data Source: Commissioners of Public Works, CFRAM, Flood Maps, available from <https://www.floodinfo.ie/map/floodmaps/>



GIS shape file displaying present high risk coastal and fluvial flooding

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: Risk analysis of the Poddle river is currently being carried out by the OPW and once complete this may influence the risk profile of the areas affected by the river.

Infr20: Redundancy

Description: this indicator measures the availability of a redundant CI

Metric(s): Availability of a redundant CI

Original reference(s) for indicator: Lhomme et al., 2013

Impact on resilience: Positive impact benefitting the local community

Data availability: This data is not publicly available

Case Study Data Source: CI provider (in discussion with water system experts)

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Infr21: Retained spare capacity

Description: this indicator measures the average operating level of assets in the area as a percentage of the maximum operating capacity

Metric(s): The average operating level of assets in the area as a percentage of the maximum possible

Original reference(s) for indicator: Rose, 2017

Impact on resilience: Positive impact benefitting the local community

Data availability: This data is not publicly available

Case Study Data Source: CI provider expertise and local news; available from <https://www.dublinlive.ie/news/dublin-news/ringsend-sewage-plant-operating-three-15913134>

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Infr22: Mitigation Plan

Description: this indicator measures availability of a local flood mitigation plan

Metric(s): Availability of local flood mitigation plan Y/N

Original reference(s) for indicator: Cutter et al., 2010

Impact on resilience: Positive impact benefitting the local community

Data availability: This data is generally available

Case Study Data Source: OPW flood information maps available from <https://www.floodinfo.ie/map/floodplans/>

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: In some instances the DCC mitigation plans were also consulted

Infr23: Previous Disaster Experience

Description: this indicator measures the history of disaster events in the CI domain

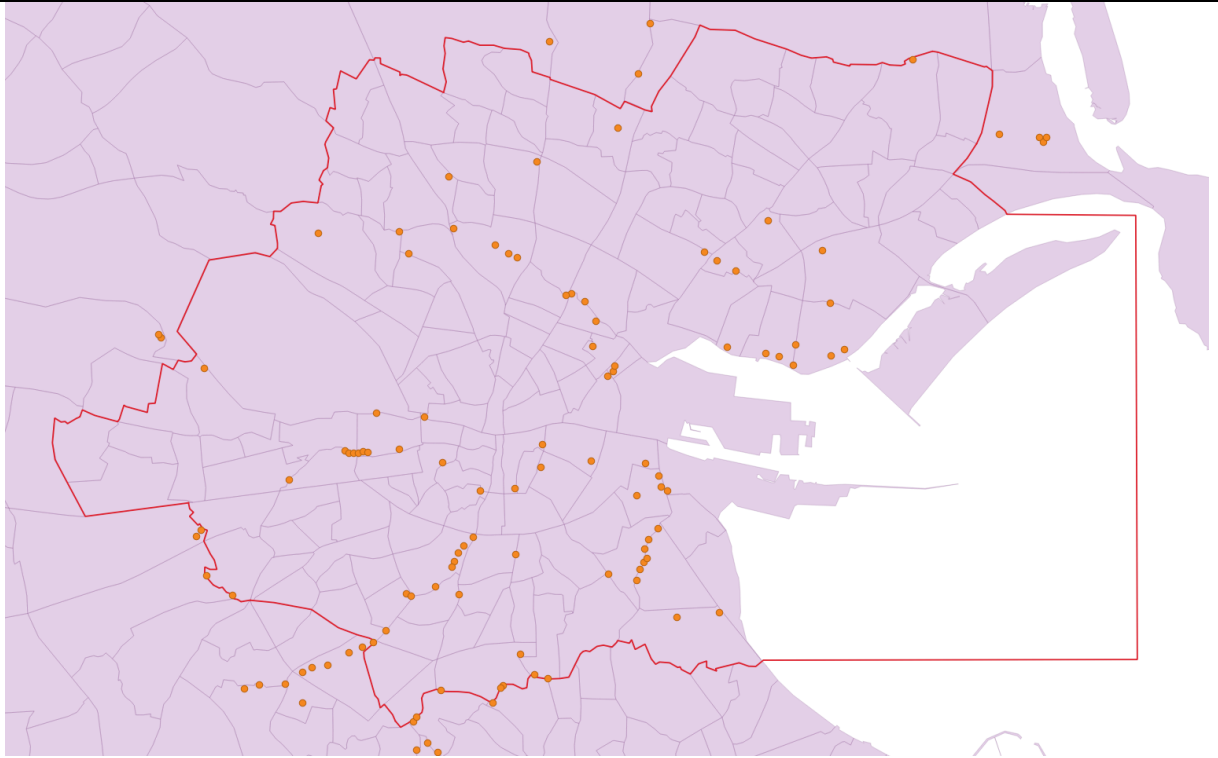
Metric(s): History of disaster events in the CI domain

Original reference(s) for indicator: Frazier et al., 2013

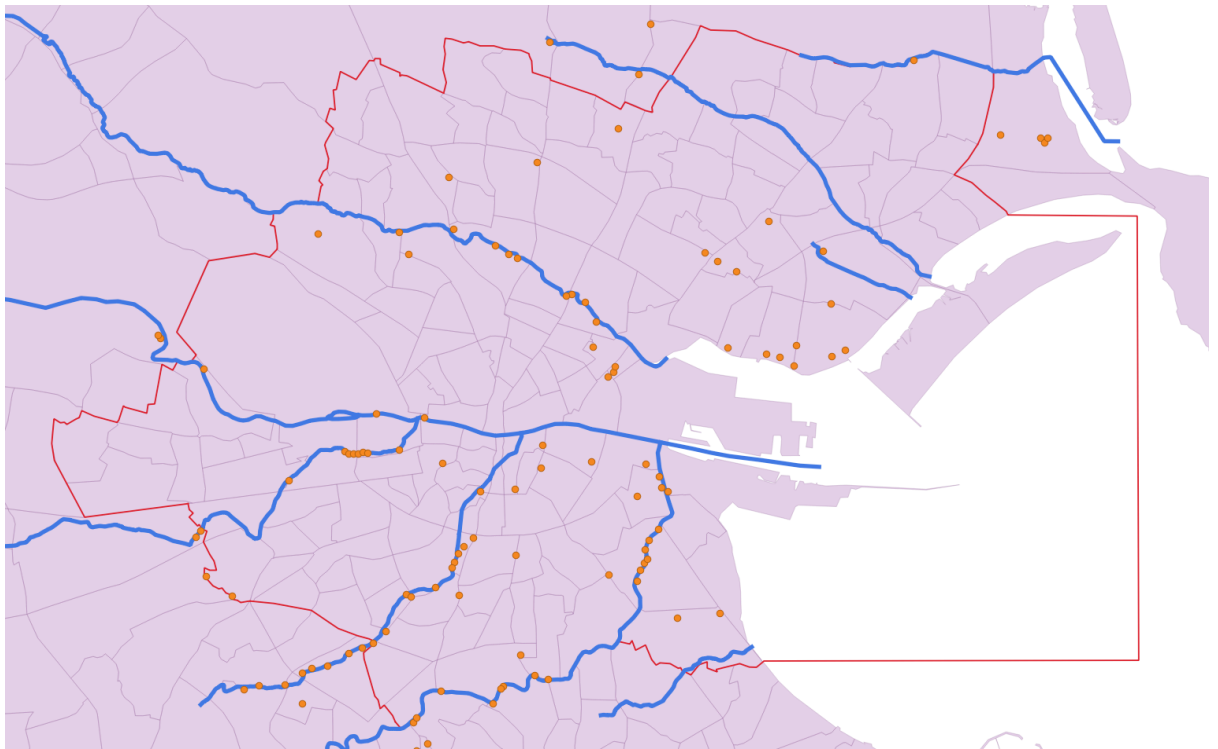
Impact on resilience: Positive impact benefitting the local community

Data availability: This data is generally available

Case Study Data Source: OPW flood information maps available from <https://www.floodinfo.ie/map/floodplans/>



GIS shape file displaying the locations of previous flood events



GIS shape file displaying the locations of previous flood events with river placement

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Infr24: Critical Assets

Description: this indicator measures the critical assets of the investigated infrastructure

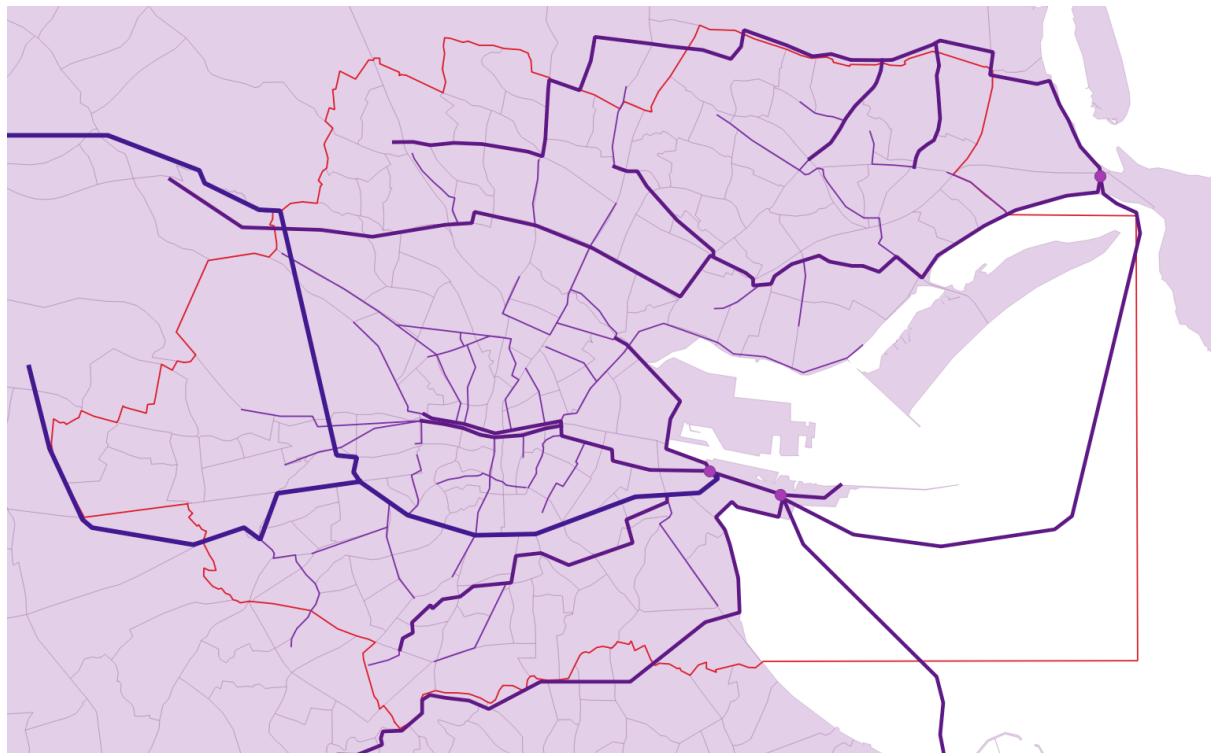
Metric(s): Critical assets of the infrastructure being investigated

Original reference(s) for indicator: Johansen et al., 2016

Impact on resilience: Positive impact benefitting the local community

Data availability: This data is generally available

Case Study Data Source: Corcoran, 2005



GIS shape file displaying arterial drainage system

Scale: Implementation is typically on a small area (i.e. a city block) or street level. It can be scaled-up to much larger scales depending on national data collection format.

Comment: NA

Consent Form

Researcher name: Conor Mark Dowling

Supervisor name: Mary Lee Rhodes

I am invited to participate in this research project which is being carried out by Conor Mark Dowling. My participation is voluntary. Even if I agree to participate now, I can withdraw at any time without any consequences of any kind.

- **PURPOSE OF THE STUDY**

The study is designed to investigate the application of urban resilience of the Dublin water management system.

- **PROCEDURES**

If I agree to participate, this will involve me being audio recorded during a semi structure interview.

- **POTENTIAL RISKS AND DISCOMFORTS**

Candidates may be uncomfortable being audio recorded, if the participant is too uncomfortable to proceed with the audio recording device on, the interview may proceed with hand written notes.

- **POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY**

This research may benefit Management, Urban Planning, Engineering, and Economic research disciplines. The research output of this research will be made available to the participant.

- **CONFIDENTIALITY AND DATA PROTECTION**

Any information or data which is obtained from me during this research which can be identified with me will be treated confidentially. The data will be kept in the researchers private files where only he will have access to it. The data storage and the grounds for

continued storage will be reviewed within 6 month of completion of data. Any data that is no longer required will be destroyed or erased in a safe and secure way. Any data that is still required will be further reviewed every 12 months and may be kept for up to 10 years.

Σ PARTICIPATION AND WITHDRAWAL

I can choose whether or not to be in this study. If I volunteer to be in this study, I may withdraw at any time without consequences of any kind. I may also refuse to answer any questions I do not want to answer. There is no penalty if I withdraw from the study and I will not lose any benefits to which I am otherwise entitled. The researcher may withdraw me from this research if my physician tells us that continued participation may injure my health.

• QUESTIONS ABOUT RESEARCH

If I have any questions about this research I can ask Conor Dowling (dowline4@tcd.ie / +353851610357). I am also free, however, to contact Mary Lee Rhodes (rhodesml@tcd.ie)

Σ RIGHTS OF RESEARCH SUBJECTS

The Trinity College Dublin School of Business Research Ethics Committee has reviewed the researcher's request to conduct this project. If I have any concerns about my rights in this study, I can contact Joseph McDonagh, Director of Doctoral Studies (jomcdonagh@tcd.ie).

Σ Signature of research participant

I understand what is involved in this research and I agree to participate in the study.

[I have been given a copy of this consent form to keep.]

Signature of participant

Date

Signature of researcher

I believe the participant is giving informed consent to participate in this study.

Signature of researcher

Date

Interview Questions

1. Spatial boundaries

1a) Are there any spatial units and boundaries outside of DCC that you think should be added or removed to the resilience study area? Please give your reasons. *(Should monitoring sites or LEAs further up-stream in the Wicklow mountains be included?)*

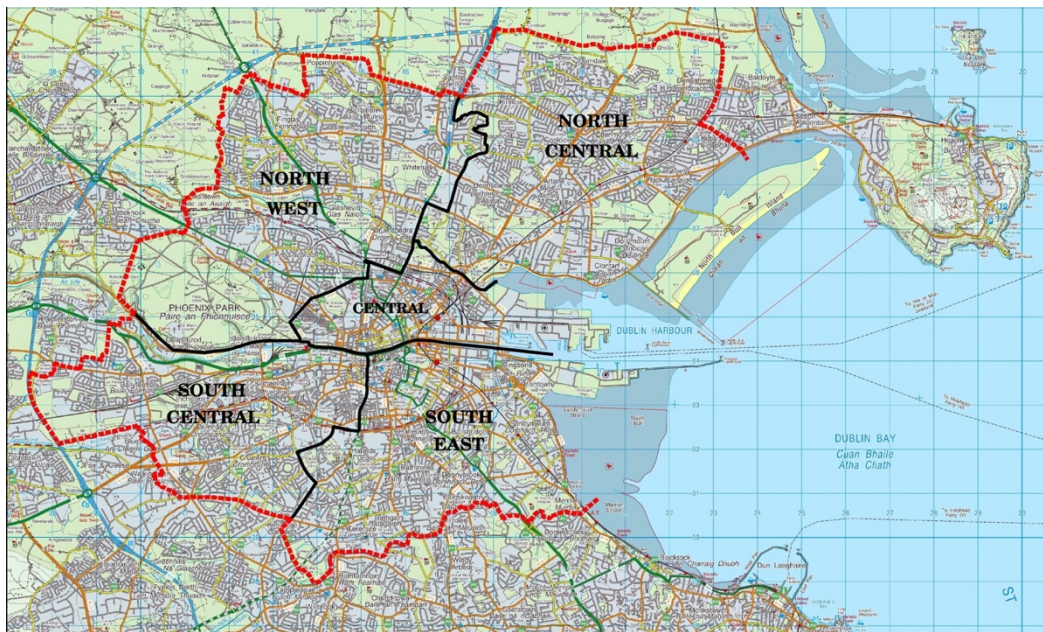


Figure 1: DCC study boundary area

1b) Do you have any other comments regarding spatial units and boundaries, boundary setting and/or the scope of the resilience analysis that you feel are relevant for this study?

2. System Boundary conditions

2a) Are there any external conditions (suggested in figure 2 below) influencing the resilience analysis area that you think should be added or removed?

2b) Of the disturbances you have listed, are there any you consider to be particularly harmful or threatening, please rank these threats?

2c) What do you consider to be the key communication flows and exchanges across the boundaries of the Dublin Water Management System? They need not be any of those suggested in Figure 2.

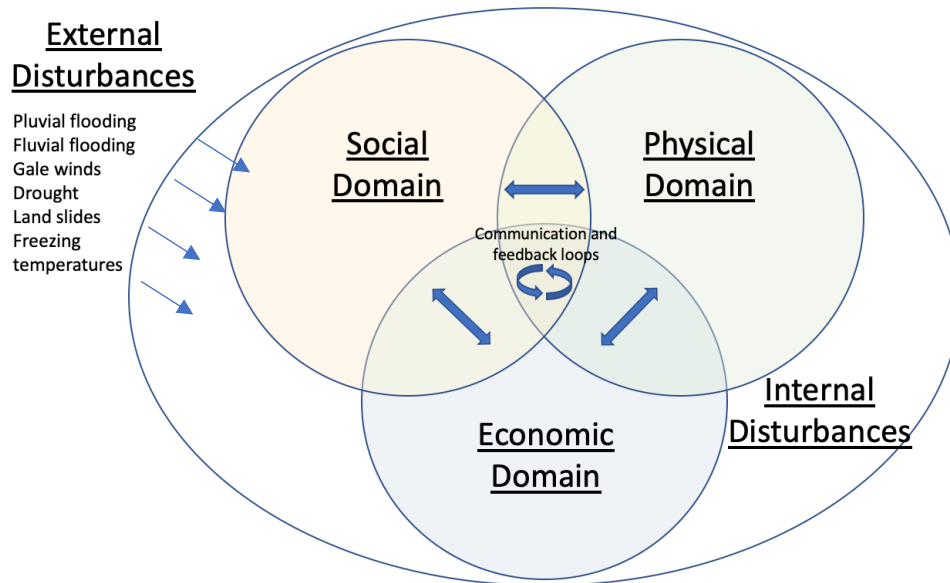


Figure 2 Conceptual model of socio technical system domains

2d) If you added or emphasised any disturbances and shock events in (2b) above: can you identify or suggest any key resulting impacts on water management infrastructure that are associated with them?

2e) Do you have any other comments regarding boundary conditions that you feel are relevant for this study?

3. Internal structure, processes and functions

3a) What do you consider to be the key assets that are found within or without the area shown in the arterial drainage map? (See our good health map for secondary example)

4c) Do you have any other comments regarding groups, networks, organisations, institutions and governance that you feel are relevant for this study?

5. Social and political capacities ('capitals')

5a) Which aspects of social capital do you consider key to the functioning of the water system? In other words what are the key relationships connecting which key groups within the macro-region? 'Key' in the sense that these are relationships that must be maintained to facilitate societal functioning, must be retained in the face of disturbances, and are important to strengthen and build in order to cope with change and recover from future disturbances.

5b) Are there any trends in the Dublin city area concerning key aspects of social capital (capacity) that you are aware of and consider to be important? E.g. significant improvements or declines in social and economic cohesiveness, cultural diversity, social cooperation, collective action, levels of participation, effectiveness of institutions and agencies, and so forth.

5c) Which key groups, networks, organisations or institutions do you consider have the greater ability and, conversely, the lesser ability to engage in political decision-making concerning and affecting the greater Dublin city area? These need not be DCC or any of those previously mentioned. Please indicate whether they have greater or lesser ability. Please give your reasons.

5d) Are there any relevant office holders, groups, networks, organisations or institutions (at whatever level) that you consider to be excluded from political decision-making concerning and affecting the resilience of water infrastructure? Please give your reasons.

5e) With increasing environmental volatility how should the governance of socio-technical systems adapt to complex disaster events?

5f) Should DCC be working more closely with other councils for flood resilience?

i. How should this be achieved?

5g) Do you have any other comments regarding social and political capacities that you feel may be relevant for this study?

6. Economic capital

6a) Are there any specific aspects of economic capital that you think should be highlighted as having a key role in the functioning of the greater Dublin city area? Key in the sense that it is an asset or capacity that must be maintained to facilitate societal functioning, must be retained in the face of disturbances, and is important to strengthen and build in order to cope with change and recover from future disturbances.

6b) Are there any trends in Dublin concerning key aspects of economic capital that you are aware of and consider to be important to this research?

6c) Do you have any other comments regarding economic capital that you feel are important for this study?

7. Socio technical systems & resilience tools

7a) Of the Resilience indicators listed below are there any which should be weighted more highly (of greater importance)?

Table 1. Resilience Indicator List

	No.	Indicator	Metric
Social Resilience	1	Educational Equity	Ratio of the pct. Population with 3rd level education to the % with no leaving certificate
	2	Unemployment rate	Percent working age population (M/F)
	3	Health	Percentage population with good health
	4	Population Coverage	Population in the area
	5	Local affluence and deprivation	Poball Haase Pratske Score
	6	Municipal Services	Proximity to fire stations
	7	Sheltering Needs	Number of hotels/hostels per square mile
	8	Voter participation	Voter participation
	9	Cultural diversity	International population
Economic Resilience	10	Owner occupied housing	Housing lived in by their owners
	11	Land value	Monetary value of system development
	12	Income and Equality	GINI coefficient
	13	Estimated Repair Cost	Monetary value of system repair
	14	Interdependencies with other urban systems	Linkages with other assets in terms of the inflows and outflows, showing the importance for the CI system network
	15	Housing Capital	available capacity
	16	Land in flood zone	At risk land as a percentage of the total study area
Critical Infrastructure Resilience	17	Risk of flooding	Local risk of flooding in the area
	18	Recovery Time	Time it takes for an infrastructure to be brought back to its pre-event level of functionality.
	19	Service Life	Quality of infrastructure is an indicator of how well an infrastructure performs (based on a 20 year avg. unless otherwise specified)
	20	Redundancy	Availability of a redundant CI
	21	Retained spare capacity	The average operating level of assets in the area as a percentage of the maximum possible
	22	Probability of failure;	Level of storm that the system can handle
	23	Mitigation Plan	Availability of local flood mitigation plan Y/N
	24	Recovery/loss ratio	Calculation of speed of recovery based on the severity of loss
	25	Previous disaster experience	History of disaster events in the CI domain

7b) In what ways, if any, can socio-technical systems be improved by applying a resilience based governance approach?

7c) What tools do you see as improving the resilience of the water system?

7d) Is the proposed use of the IoT weather sensors (river level, rain, river volume etc) realistic and of value, as a way of predicting local flooding?

- i. Is IoT a reliable communication type in comparison to other sensors?
- ii. What are the draw backs of these kind of sensors?
- iii. How does deployment of IoT sensors compare with other sensor types?

7e) Do you have any other comments regarding socio-technical system analysis that you feel are important for this study?

Appendix E IoT Sensor Readings

Figure E1 Chapelizod, River

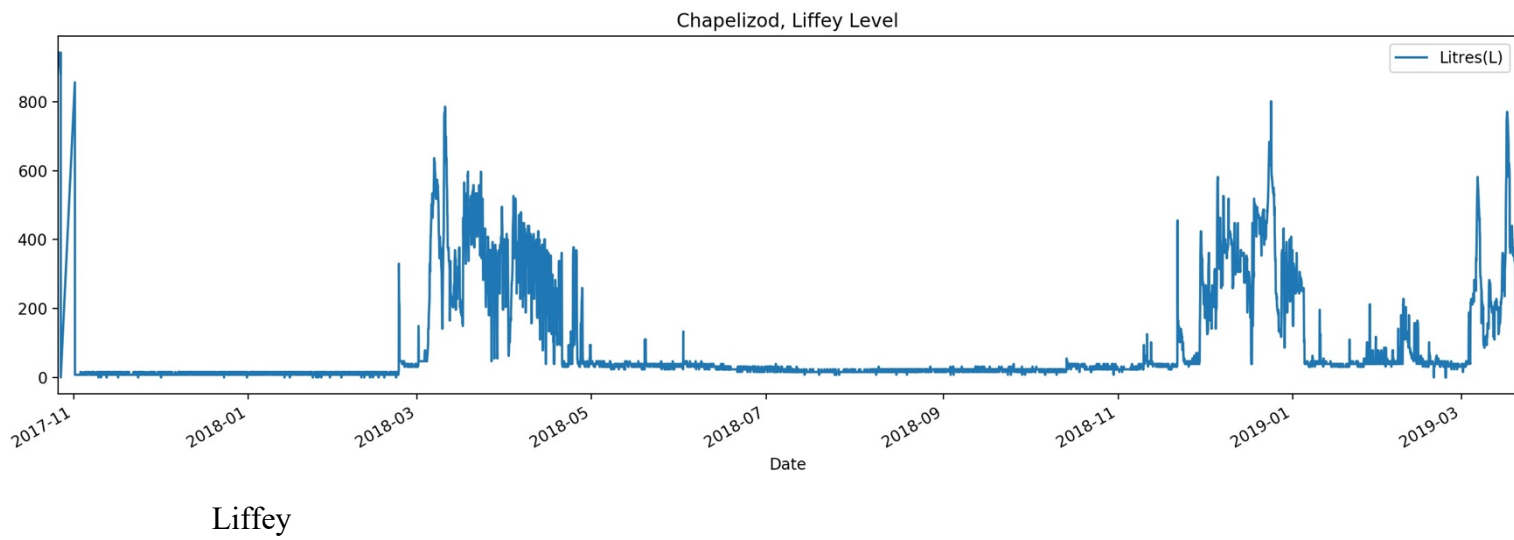


Figure E2 Cloghleagh, River

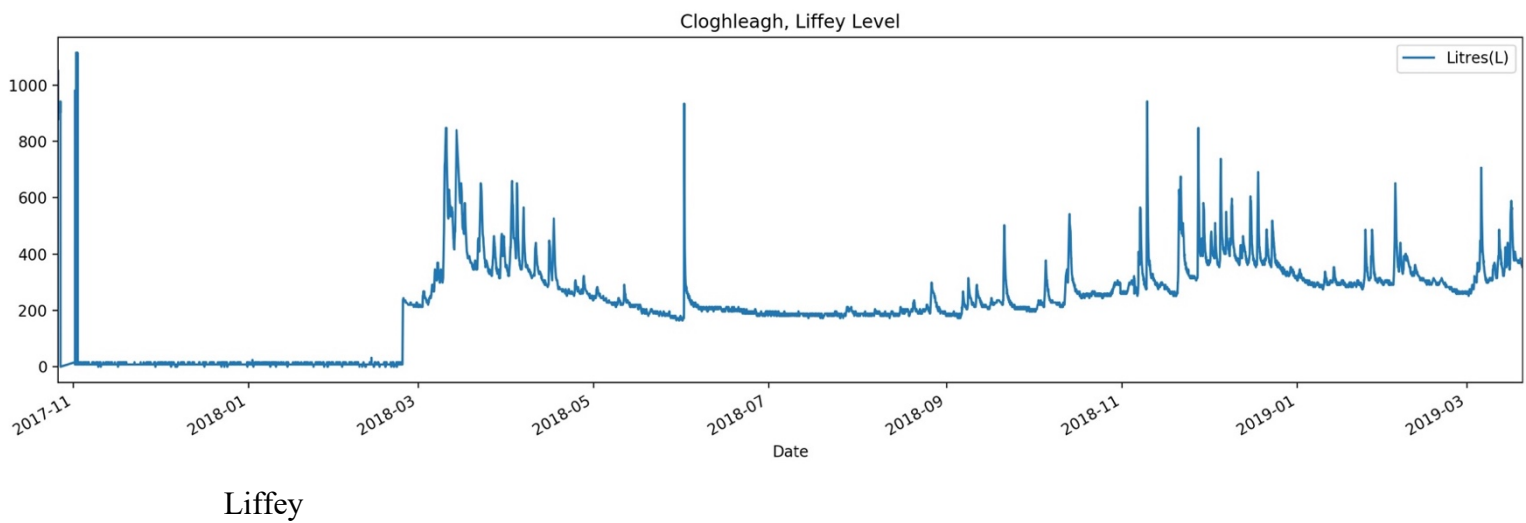


Figure E4 Bohernabreena, River Dodder

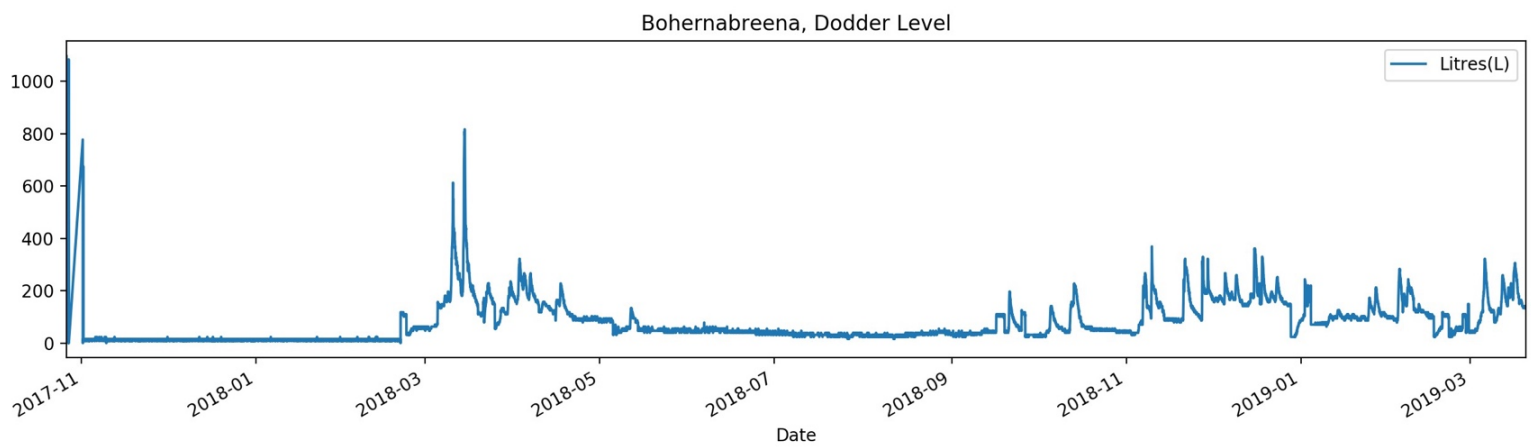
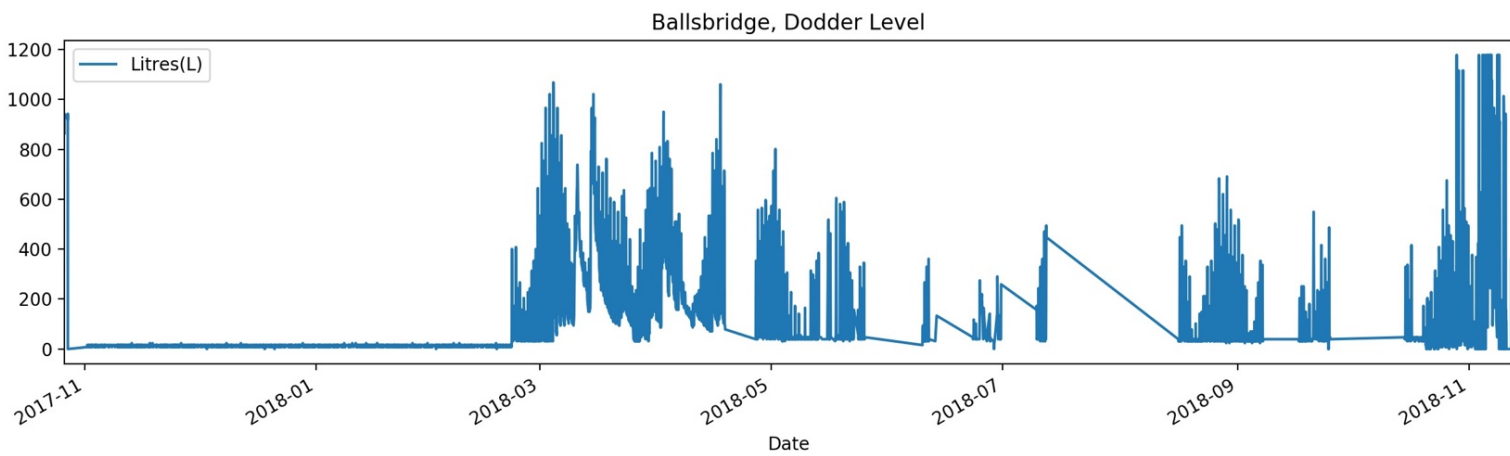
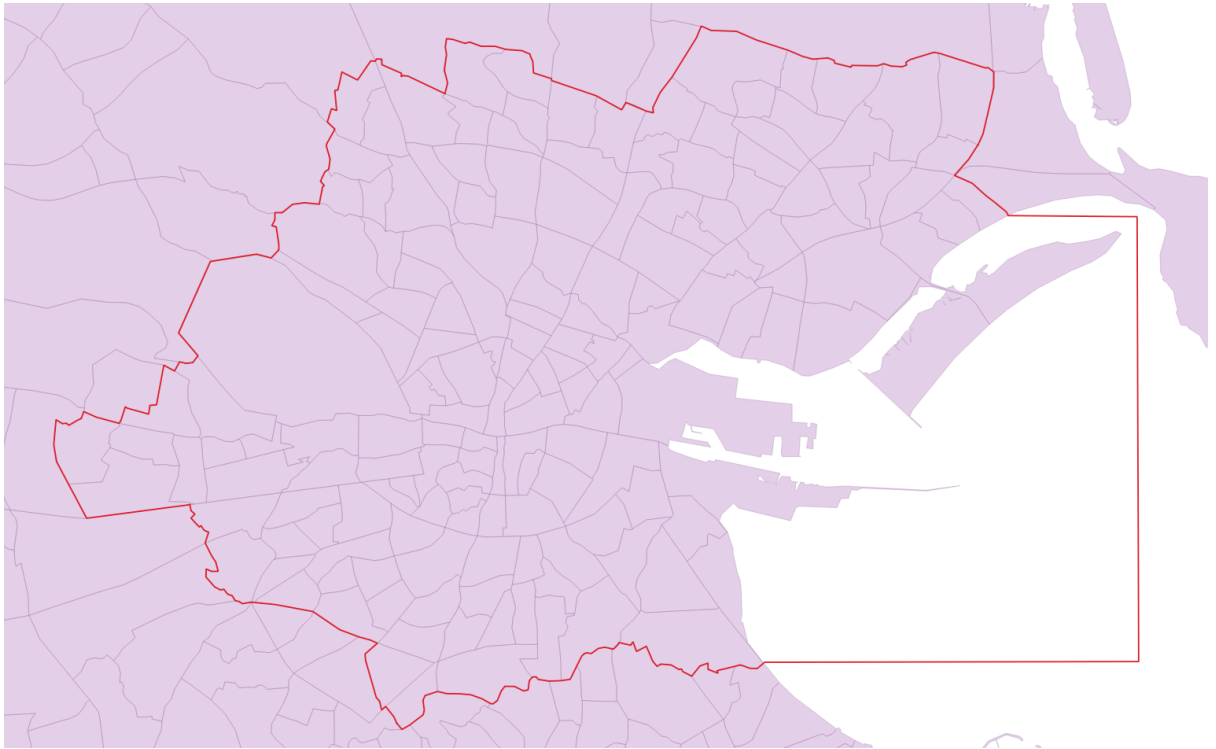


Figure E5 Ballsbridge, River

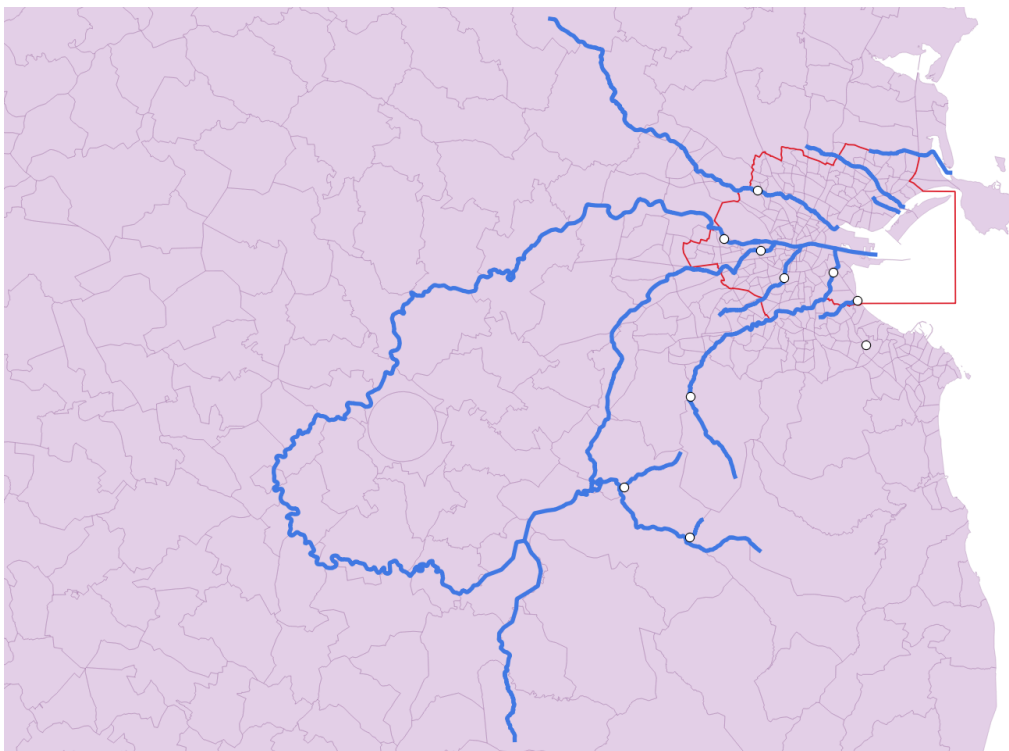


Dodder

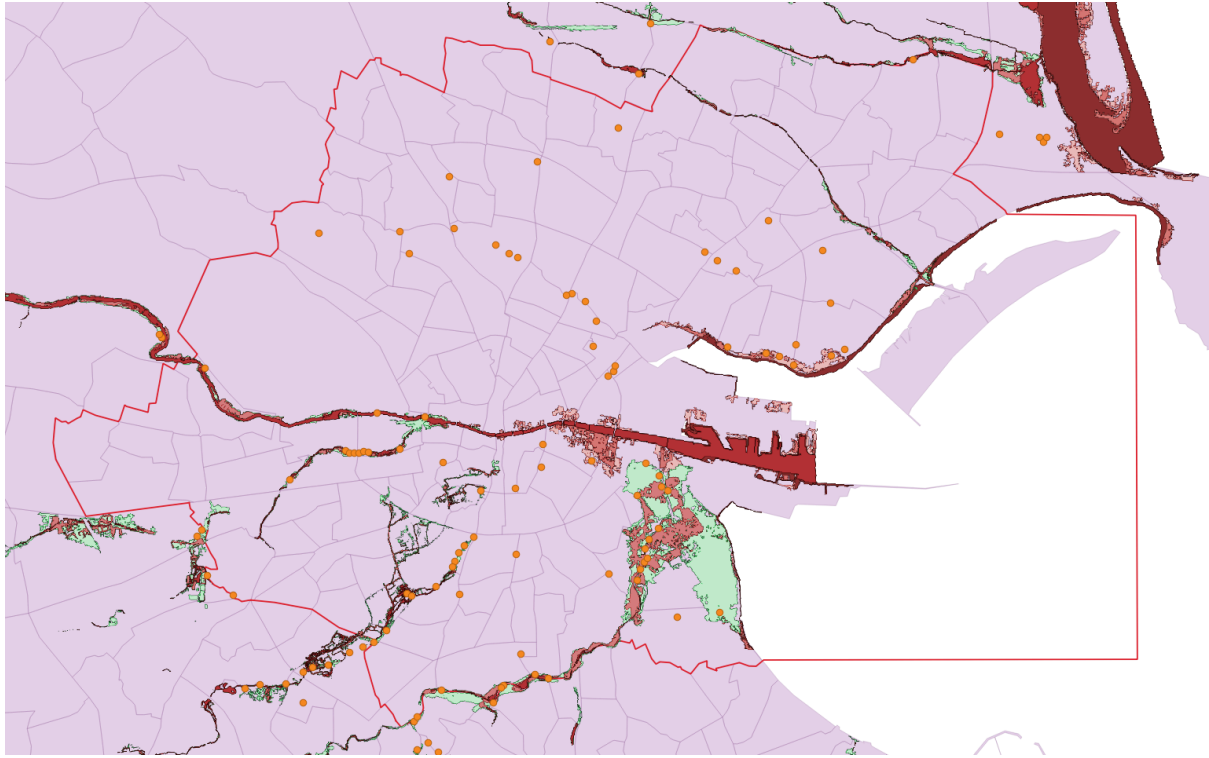
Appendix F QGIS Shape Files



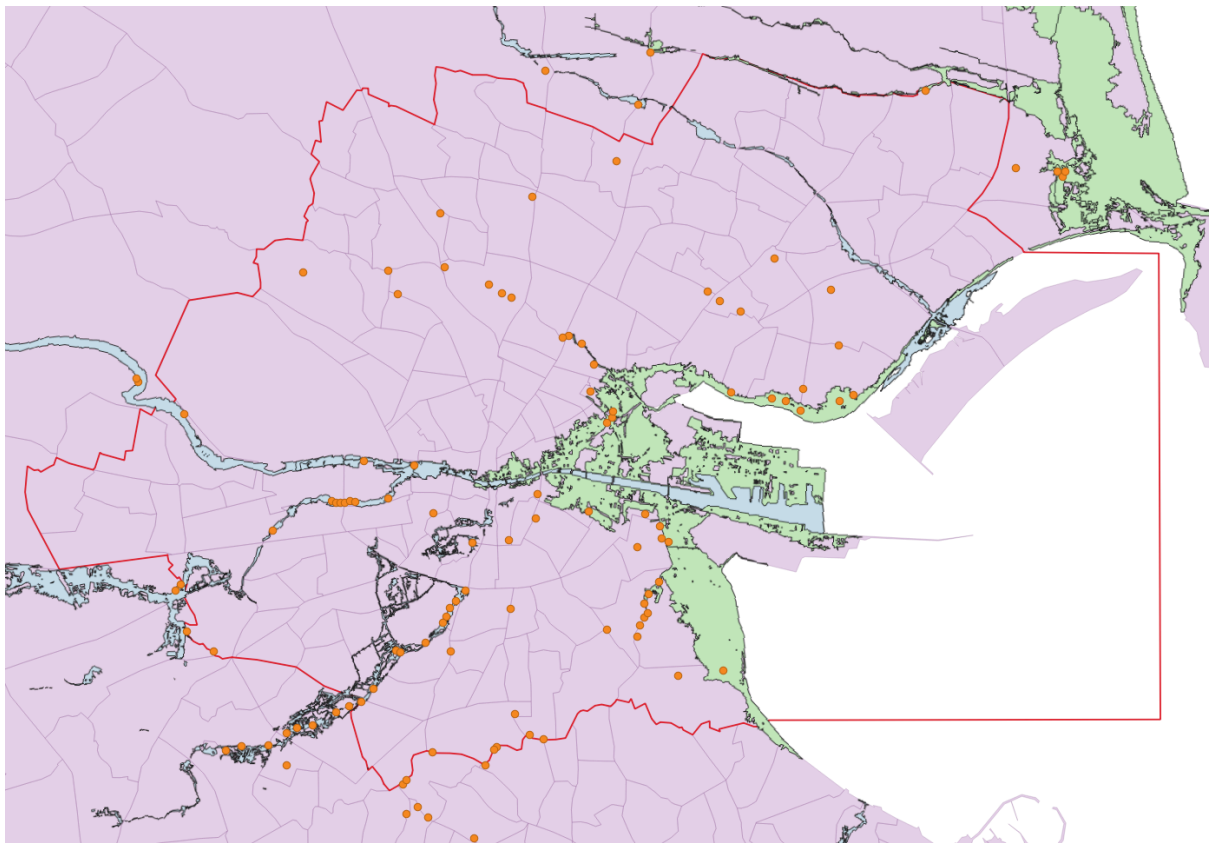
Appendix F1: GIS shape file displaying Case Study Border Area



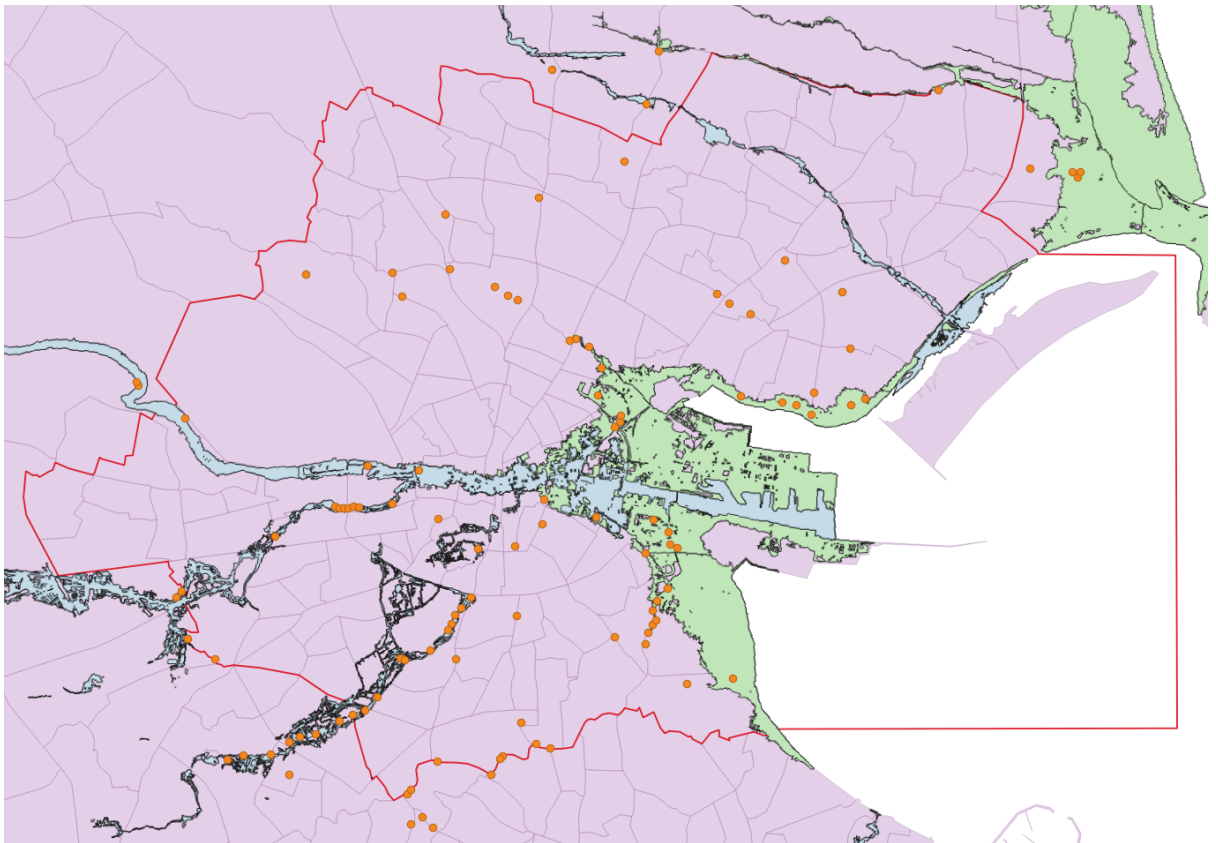
Appendix F2: GIS shape files displaying main rivers and sensor placement



Appendix F3: GIS shape files displaying previous flood event locations with future high risk coastal and fluvial flooding



Appendix F4: GIS shape file displaying previous flood event locations with future medium risk coastal and fluvial flooding



Appendix F5: GIS shape file displaying previous flood event locations with future low risk coastal and fluvial flooding