University of Strathclyde

Management Science Department

# Decision-making for climate adaptation in cities:
# Exploring challenges in practice and assessing the value of decision support methods

Eleanor Murtagh

A Thesis presented in fulfilment of
the requirements for the degree of
Doctor of Philosophy

2022

This thesis is the result of the author's original research. it has been composed by the author and had not been previously submitted for the examinations which has led to the award of a degree.



Signed: E. tagh Date: 25/02/22

## Abstract

Climate change causes wide-reaching economic, environmental, and societal impacts. Making decisions on how to adapt to climate change is vital for cities to remain viable and prosperous places to live. It is therefore imperative that local city governments must effectively identify and appraise adaptation options.

The aim of this research was to understand influences on current city-level climate adaptation decision-making practices and how decision-making may be improved through decision support methods. This thesis adopted an action research approach to study the development of Glasgow City Council's Glasgow Resilience Strategy and Climate Adaptation Strategy and Action Plan between 2015 and 2020. Data was collected through a mixed methods approach including 80 hours of participant observation, 30 hours of facilitating workshops, 28 semi-structured interviews, three expert elicitation interviews and four questionnaires.

This thesis found that adaptation decision-making was influenced by: (i) the internal and external contextual factors (limited commitment and resource); (ii) content (incomplete local data including lack of economic information); and (iii) the process of decision-making (lack of structured approach to identify and appraise adaptation options). Research suggested that these influences encouraged hypervigilance amongst decision-makers which was ill-addressed by commonly used rational decision-making frameworks for climate adaptation.

In response to the findings highlighting the lack of decision-making process, two separate decision-making methods were developed and tested as part of action research. A Bayesian Belief Network (BBN) and an adjusted Qualitative Probabilistic Network (QPN) were created to support adaptation decision-making, in relation to pluvial flooding and heatwaves respectively. Stakeholder feedback demonstrated that these methods aided understanding of the problem system, supported identification of potential adaptation actions and assisted stakeholders in considering the impact and co-benefits of possible options. Each method has strengths and weaknesses. A screening protocol was thus proposed to aid decision makers in considering when BBN or adjusted QPN methods may be most appropriate to use in practice.

# Acknowledgements

I would like to thank University of Strathclyde for funding this research and flexibility in allowing me to go part-time to further pursue my passion for climate adaptation professionally. Thanks to Dr Matthew Revie for his relentless enthusiasm for Bayesian Belief Networks, patience in explaining them to me and supporting me with my research. Thank you, Dr Grant Allan, for reviewing drafts of this thesis.

To those at Glasgow City Council who supported and partook in this research Sonia Milne, Dr Duncan Booker, Julie Robertson, and Frankie Barrett – thank you and the work of Sustainable Glasgow for making Glasgow such an incredible city.

Thanks to my Adaptation Scotland colleagues (past and present) – Kit England, Dr Joseph Hagg, Anna Beswick who have taught me so much about adaptation.

To all the people who gave up time to talk with me as part of this research, be that over coffee at a conference, participating in a workshop, sitting down for an interview - your time was valued and appreciated. Special thanks to those who work on climate and sustainability in Scotland and beyond who have encouraged this research – Dr Sarah Govan, Dr Kate Crowley, Sarah Colenbrander and Paul Watkiss.

To my friends who kept me going with words of encouragement, cards, tea, and chocolate – Dr Amy Goodwin Davies, Dr Rebecca Foster, Alison McNoughton, and Katie Elder – thank you.

To my parents Anthony Murtagh and Marian McCrudden for instilling a life-long love of learning, and to my brother Dr Tim Murtagh for reassurance throughout this process.

Lastly, to Jack, who has supported me through this long endeavour from cooking and cleaning far more than his fair share to partaking in endless conversations on climate adaptation decision-making. Thank you for your love, patience, and perseverance.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

‘What the Clyde said, after COP26’ by Kathleen Jamie (Scottish Poetry Library, 2021)

# Contents

## List of Figures

# List of Tables

## Abbreviations

| | |
|---|---|
| 100RC | 100 Resilient Cities Initiative |
| ALEOS | Arm’s-length external organisations |
| BBN | Bayesian Belief Network |
| CCP | Context, Content and Process |
| CCRA | Climate change risk assessment |
| CRO | Chief Resilience Officer |
| CPT | Conditional Probability Table |
| DAG | Directed acyclic graph |
| FRM | Flood risk management |
| GCC | Glasgow City Council |
| GHG | Greenhouse Gases |
| IPCC | International Panel on Climate Change |
| LCLIP | Local Climate Impact Profile |
| MAU | Multi attribute utility |
| MGSDP | Metropolitan Glasgow Strategy Drainage Partnership |
| M & E | Monitoring and evaluation |
| NDC | Nationally Determined Contributions |
| PBCCRD | Public Bodies Climate Change Reporting Duties |
| QPN | Qualitative Probabilistic Network |
| SCCAP | Scottish Climate Change Adaptation Programme |
| SEPA | Scottish Environment Protection Agency |
| SG | Scottish Government |
| SIMD | Scottish Index of Multiple Deprivation |
| SNP | Scottish National Party |
| UCCRN | Urban Climate Change Research Network |
| UKCIP | UK Climate Impacts Programme |
| UN | United Nations |
| UNFCC | United Nations Framework Convention on Climate Change |

# Chapter 1: Introduction to thesis

> "In this assessment of the climate change literature, a key gap…is that few reports and peer-reviewed literature, have been available that document the actual experiences and outcomes of decision-making (the actual making and implementing of decisions), the contexts in which different methods and processes were tried, and an evaluation of the costs and benefits of the approaches. As a result, there are few analyses that compare the effectiveness of different decision practices in order to identify best practice for different contexts. Unlike medical sciences, with a close interdependence between theory, research and practice and their documentation for learning and refining practices, there is a disjunct between knowledge development, decision-making and evaluation for many of the key risks."
>
> (Adler et al. in Chapter 17 of IPCC AR6 WGII (forthcoming [1]) p.31)

Climate change is a global challenge that affects the planet's ecosystems, economies, institutions, societies and citizens (IPCC, 2014b). Climate impacts will continue to define and shape society over the 21st century and beyond (Rosenzweig et al., 2010). In the recent past (the last 30 years), nations have focused on reducing emissions of greenhouse gases to address the effects of anthropogenic climate change (Nachmany et al., 2017). This targeted effort at reducing the production of greenhouse gases is commonly referred to as climate mitigation. The level of climate mitigation that was so urgently required and duly identified as needed (to stall global warming), however, has not been achieved and widespread climate impacts across the globe have already been experienced (IPCC, 2014b).

Due to the long lifespan of many greenhouse gases[2], continued warming will occur even if emissions reductions to net-zero were achieved today (which is not feasible under the current international policy commitments)[3] (Climate Analytics &

[1] I received an early draft of the IPCC Sixth Assessment (AR6) report as a reviewer in January 2021. The report is scheduled to be finalised in February 2022.
[2] Greenhouse gases have different lifespans in the atmosphere from decades (e.g. methane), centuries (e.g. nitrous oxide) or even millennia (e.g. fluorinated gases) (EPA, 2021).
[3] The unconditional pledges and targets made by international governments as of November 2021, would limit warming to approximately 2.7°C above pre-industrial levels by 2100. Thus the current policy and pledge trajectories lie well above emissions pathways consistent with the Paris Agreement long-term temperature goal of

NewClimate, 2021; Frölicher et al., 2014). Locked-in future warming means that humanity will face unprecedented climate extremes, through events such as floods, super storms, heatwaves and droughts, which are predicted to increase with further climate change (Oppenheimer et al., 2014). These climate events are already occurring with increasing frequency across the globe causing widespread human and economic losses (Gencer, 2013; Stott, 2016). Given this failure to adequately mitigate the effects of climate change through emissions reduction (and the likelihood of exacerbated impacts in the near future) it has becoming increasingly important to undertake the process of climate adaptation to prepare for current and future climate conditions (Biesbroek et al., 2009; Mimura et al., 2014). Climate adaptation relates to taking action in response to actual or expected climate stimuli to minimise the damage of impacts or take advantage of associated opportunities (Füssel, 2007b; Mcevoy et al., 2006; Noble et al., 2014). There is now increasing recognition and prominence of adaptation within policy discussions at the international and local level.

For relevant decision makers, to deliver effective adaptation, it is necessary to improve collective understanding of the complex impacts of climate change and decision-making processes needed to prevent and or minimise these impacts. One area in which climate adaptation decision-making will be particularly important is at the city level (Bulkeley, 2013). Cities are home to more than half the world's population and are often centres of economic and political activity (C40 Cities & UCCRN, 2018). Many characteristics that make global cities so prosperous (such as their dense and diverse populations, complex interconnected utilities and transport systems, and geographical locations commonly near the coast), may also make them more vulnerable to climate impacts (Moss et al., 2012).

Given that it is estimated that 68% of the world's population will be living in cities by 2050 (United Nations, 2018) it is imperative to consider urban[4] climate issues and advance climate policy discussions and actions in this area (Gencer, 2013; Hunt & Watkiss, 2011a). By not adapting to climate change, cities increase their risk of climate

---

limiting warming to 1.5°C above pre-industrial levels (Climate Action Tracker, 2020; Climate Analytics & NewClimate, 2021).

[4] Within this thesis urban and city are used as synonyms

impacts, including damage to property, business, ecosystem loss, eroded wellbeing and enhanced inequality (Revi et al., 2014). Conversely climate adaptation presents a positive opportunity and vision for how to protect and enhance natural, built, economic and social systems in the face of a changing climate.

Ensuring that appropriate city-level decision-making on climate adaptation is undertaken in a timely and well-resourced manner with options identified and appraised in a way which reduces risk and enhances resilience is paramount (Luber & Prudent, 2009; Watkiss, 2015). It is therefore important that research on this topic considers the conceptual and practical limitations of current approaches to city-level decision support in terms of restricting adaptation decision-making. Solutions to overcome these challenges must be identified and tested to ensure improved outcomes for the natural, built, economic and social systems of cities in the face of a changing climate. This thesis therefore explores the challenges influencing current city-level climate adaptation decision-making. It subsequently trials and considers the value of two decision support methods to address identified challenges. This thesis argues that city-level adaptation decision-making processes remain ad-hoc and are ill supported by common guidance and decision support methods, despite the importance of the resulting decisions.

The first section in this chapter, Section 1.1 explores the rationale for exploring climate adaptation decision-making in cities. Subsequently, Section 1.2 outlines the aims and objectives of this thesis. Section 1.3 introduces research approach to achieve objectives. Section 1.4 details the thesis structure and the contents of each chapter within the thesis. Finally, Section 1.5 summarises presentations and publications completed during this PhD.

## 1.1 Thesis rationale: The need to understand climate adaptation decision-making in cities

The rationale for this research derives from the necessity to ensure that organisations, in particular local authorities such as city councils, are able to make informed, considered, effective and appropriate decisions on climate adaptation. Although there are numerous tools, methods and processes developed both in academic literature and practice to aid the climate adaptation decision-making process, very little in-depth research has been conducted on the practical value of these processes when applied in a ‘messy’ real world setting by city authorities (Capela Lourenço et al., 2014; Daddi et al., 2018). In particular, there exists a plethora of adaptation guidance and frameworks which adopt a risk-based cycle framework premised on the concept of rational decision-making, such as the Adaptation Wizard (Willows & Connell, 2003), Klimatlose (Webb & Beh, 2013) and the RESIN Framework (Chapman, 2018). Despite their relative popularity having been referenced widely in the literature (Brown et al., 2011; Webb & Beh, 2013; Palutikof et al., 2019), there are limited critiques of whether these guidance documents and conceptual framings are reflective of, or indeed supportive for, adaptation decision-making at the city level.

A critical review of widely adopted processes for climate adaptation decision-making is important for several reasons. Firstly, Arnell (2010) and Capela Lourenço et al. (2015) outline that there is a significant knowledge gap surrounding challenges of making adaptation decisions in real life settings. Management scientist Andrew Pettigrew’s research on organisational change and decision-making has identified the importance of (i) the context in which the decision maker was operating, including national policy influences and organisational attributes; (ii) the process of decision-making and options evaluation including the guidance and steps used and decision support systems or lack thereof; and (iii) the content (the data and evidence) used (Pettigrew, 1990). This is pertinent to climate adaptation decision-making given the range of articles highlighting the barriers to adaptation in practice (Eisenack et al., 2014; Moser & Ekstrom 2010a; Oberlack, 2017). There is, however, a need to explore and unpack the *drivers* of barriers to adaptation, delving deeper than the simple listing of barriers which is common in the literature (Biesbroek et al., 2015).

Mustelin et al. (2013) also note, that whilst there has been a rapid proliferation of climate adaptation research advancing theoretical and conceptual understanding of adaptation, there remains a substantial gap in applying such theoretical frameworks and tools in policy and practice. Adaptation planning in practice is often under-developed, under-resourced and focused on quick wins rather than the implementation of sufficient adaptation actions (Berrang-Ford et al., 2011; Jones et al., 2014). As a result of these constraints, Capela Lourenço et al. (2015) suggests that current decision support methods (such as those based on the Adaptation Wizard) are becoming increasingly unsuitable and new decision-making approaches that take account of these realities are necessary.

Secondly, there remains a lack of consensus in the literature as to which decision-making methods are robust and applicable to adaptation particularly at the city level (Mustelin et al., 2013). According to Siders and Pierce (2021, p.5) “the field needs more research on how decisions are actually being made and on how decision-makers should select an appropriate decision-making strategy”. As a result, there is an identified need for further research on approaches to assess adaptation options (Capela Lourenço et al., 2014; Siders & Pierce, 2021; Tompkins et al., 2010).

Thirdly, cities have an important role to play in adapting to climate change and possess unique decision-making contexts. Factors which can relate to local authority climate adaptation decision-making generally include inflexible governance structures, required provision of service delivery, devolved responsibilities for climate action, reduced budgets as a result of austerity and restricted policy-making abilities (Bulkeley, 2010; Heald & Steel, 2018). As a result of these factors, there is often an “adaptation deficit” between needed levels of adaptation and the level of adaptation achieved in practice (Ekstrom & Moser, 2014). It is therefore evident that a detailed evaluation of the normative conceptual and methodological framings that support real-world city-level climate adaptation decision-making is needed to determine to what extent cities’ climate adaptation decision-making processes influence decisions being made and how these processes could be improved. Whilst climate adaptation decision-making is evidently a global topic, this research focuses on one city for in-depth data collection and analysis.

## 1.2 Thesis aim and objectives

Although climate adaptation decision-making processes have advanced conceptually, their level of utility when applied in practice, particularly at the city level, is yet to be fully understood. The aim of this thesis, therefore, is to address this knowledge gap by undertaking action research with a city council (Glasgow, Scotland)[5] to understand current decision-making processes for climate adaptation. The thesis studied influences on climate adaptation decision-making in practice. Through identification of deficiencies in current approaches and a lack of decision support methods used in decision-making, the methods of Bayesian Belief Networks (BBNs) and adjusted Qualitative Probabilistic Networks (QPNs) were then developed, to assess their ability to address challenges influencing current decision-making.

At the broadest level, the aim of this thesis is to analyse climate adaptation decision-making in Glasgow, guided by the fundamental research question: What challenges influence city-level climate adaptation decision-making currently and what is the value of using alternative decision support methods? Decision support methods can aid the way in which decisions are made, and/or improve the outcomes of the decision (Phillips-Wren et al., 2011). Value is thus defined within this thesis as the usability and usefulness of the method and the resulting benefit of the process and/or output to decision-making. Value is assessed in relation to the identified challenges in the decision-making context, as well as the content (data and information) required, and process undertaken.

The following objectives were used to achieve the aim of the thesis:

**Objective 1:** Identify the challenges influencing current city-level adaptation decision-making within the real-world context of a city council developing an adaptation strategy and action plan.

To achieve this objective, the following sub-objectives were pursued:

- Identify influences arising from the context, content and process affecting decision-making in Glasgow
- Situate the findings in the wider literature on decision-making to identify common challenges and potential solutions

[5] Glasgow City Council is one of Scotland's 32 local authorities (Scottish Government, 2020a)

**Objective 2:** Assess the value of Bayesian Belief Networks (BBNs) and adjusted Qualitative Probabilistic Networks (QPNs) as decision-making methods to support climate adaptation decision-making within a city council and address challenges identified via Objective 1.

To achieve this objective, the following sub-objectives were pursued:

- Develop and test BBN and QPNs for enhancing resilience to pluvial flooding and heatwaves respectively
- Compare and contrast BBNs and QPNs in relation to challenges arising from the context, content and process identified in Objective 1
- Use findings to design a protocol to enable decision makers and researchers to consider when the use of a BBN or QPN may be most appropriate

## 1.3 Research approach to achieve objectives

An action research approach was developed to achieve Objectives 1 and 2. This thesis draws inspiration from Patwardhan et al. (2009, p.219) who outline that:

> "in order to address science and research needs, an integrated approach is necessary, one that combines new knowledge with new approaches for knowledge generation, and where research and practice co-evolve; and that such a learning-by-doing approach is essential to rapidly scale up and implement concrete adaptation actions".

Action research was adopted as the main research approach for the following reasons:

1. It enables observations and involvement in lived experience of undertaking decision-making which produces valuable knowledge that cannot be gleaned from other methods (such as interviews and questionnaires alone);
2. It provides access to closed-door meetings and off the record conversations which illustrates the social and political context surrounding decision-making.

Research explores, from a climate adaptation perspective, how management science methods can be applied to the field of adaptation. This thesis was written by an adaptation practitioner currently working in Scotland. Some sections of this thesis, where appropriate, are written in the first person.

A further description of what action research is, why it was used, and limitations and benefits are described in Section 4.1.3 and Section 4.1.4. To conduct action research, the research objectives were explored via study of Glasgow City Council (GCC), as described in Section 4.3.4. The focus on one city was a conscious decision, as it was seen as necessary to invest the time and effort to build the intimate relationships needed for effective action research, understand real-life decisions, and experience the entirety of the decision-making process. Section 1.4 provides an outline summary of the structure and content of the thesis.

## 1.4 Thesis structure

This section presents how the thesis is structured to achieve the stated thesis aim and objectives (detailed in Section 1.2). The remaining chapters of the thesis are introduced and summarised here. A summary of chapters is represented in Figure 1.1.

Chapter 2 introduces the topic of climate change and describes the two main approaches to address it, mitigation, and adaptation. The chapter then provides an overview of climate adaptation terms and outlines varying adaptation typologies. The role and remit of cities in preparing for and adapting to climate change is also discussed. The chapter concludes by highlighting challenges currently restricting progress on city-level adaptation, including lack of resources, challenges in understanding climate science, lack of leadership and difficulty in identifying which of the many climate adaptation guidance resources and decision support tools are most appropriate in guiding city level adaptation decision-making.

Chapter 3 explores common methodological practices for climate adaptation decision-making. Attributes of the adaptation decision-making context, including complexity and uncertainty, are reflected upon, before a review of methods to support adaptation decision-making is undertaken. After reviewing common decision frameworks (such as the Adaptation Wizard) and methods (such as cost-benefit analysis, multi-criteria decision analysis, system dynamics and Bayesian Belief Networks), the chapter

identifies the key knowledge gaps relating to how adaptation decisions are made in practice and the clear need for further study on the usefulness of decision support methods.
Chapter 4 explains the research design underpinning this thesis. The research methodology of action research is outlined. The research context of Glasgow City is then introduced. In addition, the structure, organisational aims and objectives, department, legislative mandate, and powers of GCC are detailed.

Chapter 5 presents the methodology, methods and analysis used to achieve Objective 1. The chapter provides an overview of the mixed methods approach used including data collection through participant observation, media analysis, semi-structured interviews, questionnaires and workshops.

Chapter 6 addresses research Objective 1 which was to identify the challenges of current adaptation decision-making within the real-world context of a city council developing an adaptation strategy and action plan. The findings from observing GCC's development of the Glasgow Resilience Strategy and Climate Adaptation Strategy and Plan, from September 2015 to February 2020 are presented. The chapter discusses the empirical data collected from 200 hours of action research including participation observation and 27 semi-structured interviews with 38 stakeholders involved in GCC's climate resilience and adaptation efforts. Findings indicate that challenging influences arising from the context, content, and process, led to a state of hypervigilant decision-making. Hypervigilance is where the decision-maker did not canvas all potential options nor assess them thoroughly due to a perception of lack of time and resource. The chapter concludes by highlighting the need for the consideration of alternative approaches to decision-making process to address hypervigilance. The identified need for approaches with properties that incorporate uncertainty, are accessible, and do not require substantial resource commitments lay the ground for the exploration of BBNs and QPNs.

Chapter 7 outlines the methodology used to address research Objective 2, which was to assess the value of Bayesian Belief Networks (BBNs) and adjusted Qualitative Probabilistic Networks (QPNs) as decision-making methods to support climate adaptation decision-making within a city council and address challenges identified via Objective 1. The steps undertaken to develop and assess both the BBN and QPN are presented.

Chapter 8 presents research on Objective 2. It addresses the challenges to decision-making identified in Chapter 6 by developing, implementing, and evaluating the usefulness of BBNs in the context of flood resilience. The advantages and limitations of BBNs to climate adaptation are then explored. Findings highlighted that the elicitation burden and technical requirements of BBNs was restrictive, as such a second study was developed to assess an alternative approach.

Chapter 9 explores the use of QPNs as a decision support method. A QPN was used to help identify and appraise options in relation to the context of heatwaves. The identified benefits and limitations of QPN to climate adaptation decision-making are then presented.

Chapter 10 combines the findings from Chapters 8 and 9 to assess the value of BBNs and QPNs in relation to climate adaptation decision-making. Value is defined in relation to the context, content and process influences as identified in Chapter 6. A protocol to support decision makers and researchers in assessing when BBNs or QPNs may be applied is then introduced.

Chapter 11 concludes the thesis. The chapter reflects on the findings and contributions of this research. Areas for further work and research are identified, including further study on hypervigilant decision-making, exploration of complementary methods to accompany BBNs and QPNs in adaptation options appraisal and the need for additional empirical studies of adaptation decision-making.

Figure 1.1 provides a schematic summary of thesis structure. As illustrated, Chapters 5 and 6 address research Objective 1 specifically and Chapters 7, 8 and 9 address research Objective 2 specifically. The remaining chapters are crosscutting contributing to the overall research aim and both objectives.

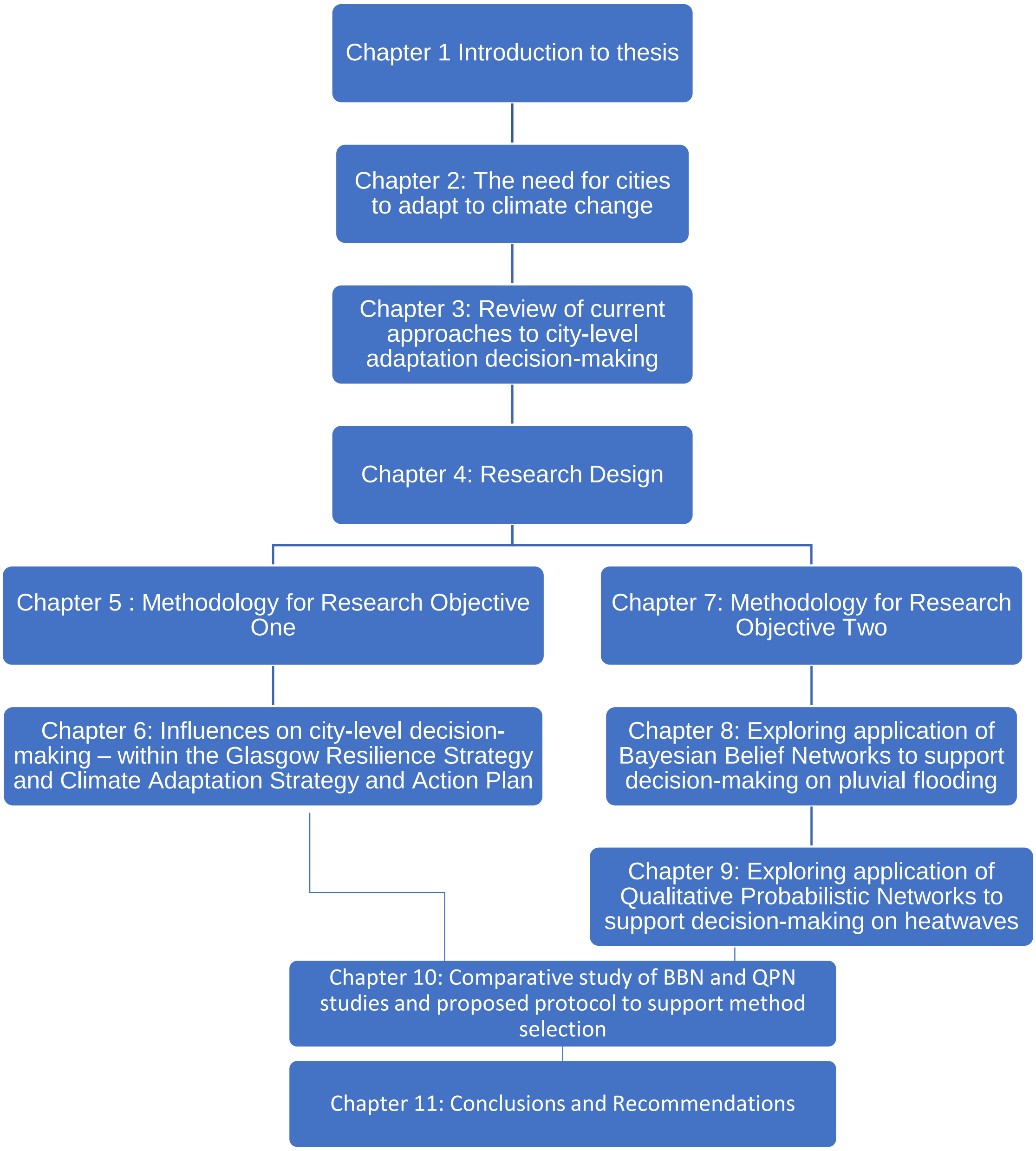



*Figure 1.1: Schematic summary of thesis structure.*

## 1.5 Presentations and Publications

During this PhD (which was completed part-time), emerging research was presented at relevant conferences. Presentations included:

- World Forum on Climate Justice: 19th-21st June 2019. Presentation Title: 'Addressing climate disadvantage in the post-industrial city - lessons from Glasgow'.

- 4th European Climate Change Adaptation Conference. May 2019. Lisbon, Portugal. Presentation Title: 'Exploring the Utility of Bayesian Belief Networks for Climate Adaptation Decision-making: Insights from Glasgow, UK'

- 3rd European Climate Change Adaptation Conference. May 2017. Glasgow, UK. Presentation Titles: 1. 'Does size matter? Assessment of Scale and Governance Issues for City and Regional Climate Adaptation Frameworks: Case Study of Glasgow' and 2: 'Local Climate Impacts Profile across Sectors – Requirements for Buy-in from the 'Unusual Suspects'

- Data and Cities as Complex Adaptive Systems (DACAS) Workshop. June 2016. Sao Paolo, Brazil. Presentation Title: "Complexity Science & Climate Resilience"

In addition, during this research period the following publications were authored or co-authored:

- Naylor, L. A. , Murtagh, E. And Kippen, H. (2019) Our 'Dear Green Place': Glasgow's transformation from industrial powerhouse to sustainable city. In: Kintrea, K. And Madgin, R. (eds.) *Transforming Glasgow: Beyond the Post-Industrial City.* Policy Press: Bristol. ISBN 9781447349778

- Murtagh, Ellie & Lane, Matthew. (2021). Putting the 'Place' in Place-Based Climate Action: Insights from Climate Adaptation Initiatives Across Scotland. 10.1007/978-3-030-79739-3_2.

This thesis does not contain content of all of these presentations and publications, given that not all directly related to the identified research objectives. The learning from the development of these outputs, however, did inform researcher development and growth.

# Chapter 2: The need for cities to adapt to climate change

> "The international climate science research community has concluded that human activities are changing the Earth's climate in ways that increase risk to cities…Cities and their citizens already have begun to experience the effects of climate change. Understanding and anticipating these changes will help cities prepare for a more sustainable future. This means making cities more resilient to climate-related disasters and managing long-term climate risks in ways that protect people and encourage prosperity."
>
> (Rosenzweig et al., 2015, p.1)

This chapter outlines, through a literature review, the contextual setting with which this thesis is embedded. Firstly, it introduces the process of global climate change and outlines the consequences it has and will have on society (Section 2.1). Secondly, the two main approaches to tackling climate change, mitigation and adaptation are presented (Section 2.2 and Section 2.3 respectively). Section 2.4 then outlines why further attention and research on climate adaptation is required and provides detailed background on the history and theoretical foundations of climate adaptation. The importance of climate adaptation in cities is explored in Section 2.5. Current knowledge gaps and research opportunities pertaining to how cities can adapt to climate change are outlined in Section 2.6, and Section 2.7 concludes the chapter by providing a summary.

## 2.1 What is climate change?

Climate change is one of the greatest threats to humanity, as it impacts societies, economies and ecosystems across the world (Hoegh-Guldberg et al., 2018; Oppenheimer et al., 2015; Rosenzweig et al., 2015). This section outlines what climate change is and provides background for the rest of the chapter.

The term 'climate change' refers to alterations in the earth's climate over long periods of time. A commonly used definition of climate change is provided by the Intergovernmental Panel on Climate Change (IPCC)[6] which defines it as:

> "a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer" (IPCC 2018, p.544).

The climate can be altered by several different mechanisms. Climate change can be caused by natural processes like volcanic eruptions and external forcings such as alterations of the solar cycles. The climate can also be affected by human activities including industrial processes and agriculture which produce greenhouse gases (GHGs)[7], and cause changes to the composition of the atmosphere (IPCC, 2018).

Anthropogenic global warming, the temperature increase caused by human activities, has already resulted in approximately 1.0°C of warming on average across the planet above pre-industrial levels (Allen, et al., 2018). Whilst 1.0°C may not sound like a significant increase, it has already resulted in a wide range of environmental, social and economic impacts (Rahmstorf, 2008). Environmental impacts range from the Arctic ice melting, sea levels rising, oceans warming and acidifying to more intense and frequent extreme weather events such as storms and drought (IPCC, 2014d). These environmental impacts ultimately result in social and economic impacts. An example of social impacts could be the increasing frequency of heatwaves which leads to increased deaths and climate induced migration (Met Office, 2019). Economic impacts may relate to the financial costs of extreme weather events such as flood, severe storms, and drought. These impacts are predicted to increase or intensify as climate change continues (Hoegh-Guldberg et al., 2018).

---

[6] The United Nation's body for assessing the science related to climate change. Section 1.1 aims to provide an introduction to climate change for those unfamiliar with the topic and therefore utilizes IPCC references regularly given the organisation's credibility in providing peer-reviewed summaries of climate science.

[7] Greenhouse gases are gases that exist in Earth's atmosphere. Examples include water vapour, carbon dioxide, methane, and nitrous oxide. These gases make the planet's surface warmer because they absorb and emit heat energy (including downwards back to the ground). Their presence makes Earth habitable. Greenhouse gases emitted as a result of human activities, however, changes the planet's energy balance and thus its climate (Schneider, 1988).

Although 1°C of warming has occurred globally to date, a median warming of 2.6-3.1°C by 2100 is projected (Climate Action Tracker, 2020; Rogelj et al., 2016). This additional warming is important as climate impacts are influenced by the extent of climate change occurring. The IPCC (2018) found that even 1.5°C of global warming will result in extreme temperatures, drought and increases in frequency, intensity and/or amount of heavy precipitation in several regions. Increasing global warming will also accelerate species loss and extinction. For example, it is projected that the number of species to lose over 50% of their climatically determined geographic range would be 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming, with that increasing to 18% insects, 16% of plants and 8% of vertebrates in a 2°C warmer world (Hoegh-Guldberg et al., 2018).

The IPCC anticipate that warming above a 2°C threshold would be very difficult for societies and ecosystems to deal with and beyond this threshold, natural systems may transform into new states (IPCC, 2018). Examples include permafrost loss, amazon rainforest die-back or coral reef die-off. When such thresholds are crossed the consequences for the climate are unclear due to the complexity of feedback loops (Drijfhout et al., 2015). An example of a self-reinforcing feedback loop is the melting of the arctic permafrost. This will release millions of tonnes of methane which increases global temperatures, subsequently accelerating permafrost melting. Self-reinforcing feedback loops could push the Earth System past a planetary threshold that would result in runaway global warming in a "Hothouse Earth"[8] pathway, even as mitigation measures continue (Steffen et al., 2018).

Limiting global warming to 1.5°C, however, is anticipated to significantly reduce these impacts. Keeping temperature increases below 1.5°C is thus a global policy priority, as evidenced by the United Nations (UN) Paris Climate Agreement. The Paris Climate Agreement is a legally binding international treaty on climate change, which was adopted by 196 nations in 2015. The goal of the Agreement is to limit global warming below 2°C and preferably 1.5°C compared to pre-industrial levels. To achieve this

[8] The Hothouse Earth concept is based on a study (Steffen et al., 2018) that proposes with climate change of 3 or 4°C, Earth's "self-reinforcing feedbacks" that occur (including wildfires, methane release, forest loss) may actually increase the temperature even more. This may lead to a 'runaway' and 'nonlinear process' of climate change that no amount of human intervention can mitigate.

goal, nations have agreed to limit their production of greenhouse gas emissions. In addition to emissions reductions, nations have committed to prepare for current and projected climate impacts. Such actions to address climate change are often described as two types of approach, climate mitigation or adaptation (Klein et. al., 2005; Tol, 2005). The Paris Agreement Article 7 requires nations to undertake both mitigation and adaptation action, however the focus to date has been primarily on mitigation (United Nations, 2015).

Climate mitigation refers to reducing greenhouse gas emissions to limit future global warming, whilst climate adaptation relates to taking action in response to actual or expected climate stimuli to minimise the damage of impacts or take advantage of associated opportunities (Füssel, 2007b; IPCC, 2014d; Mcevoy et al., 2006). The following sections (Section 2.2 and Section 2.3) presents the two approaches of mitigation and adaptation respectively. This chapter does not provide an overview of climate science or go into significant detail on climate trends and projections as this is out with the scope of this thesis. For comprehensive summaries on climate science and climate projections, please refer to IPCC (2014, 2018), Met Office (2018), King (2004) and Oreskes (2005).

## 2.2 Climate mitigation

Climate mitigation aims to slow the rate of climate change through the reduction of greenhouse gas emissions (GHGs) (IPCC, 2014b). Mitigation is essential to prevent or at least minimise mass destabilisation of natural and built habitats and societies which would become a reality with unfettered climate change (Blanco et al., 2014). Examples of mitigation actions include switching from fossil fuels to renewable energy, reducing aviation travel, insulating buildings and introducing active travel infrastructure for pedestrians and cyclists (Lamb et al., 2019; Skea & Nishioka, 2008).

Although critical, action on mitigation globally remains inadequate with regards to avoiding catastrophic climate change. Internationally, nations have committed to the Paris Climate Agreement which mandates reducing global emissions of greenhouse gases by 40% by 2030, where each nation plans how to reduce their own territorial emissions, known as Nationally Determined Contributions (NDC) (United Nations, 2015). As highlighted, current NDCs are insufficient to maintain global average temperature increases to below 2°C and are estimated to result in a median warming of 2.6°-3.1° C by 2100 (Climate Action Tracker, 2020; Rogelj et al., 2016). Increased ambition and action are therefore still required internationally to remain within 2°C of warming.

Through reducing greenhouse gas emissions, mitigation also only addresses future climate impacts. Climate change, however, is already resulting in impacts which are being felt around the globe. These impacts are predicted to continue for the rest of the century even if mitigation targets are achieved, due to the long lifespan of some greenhouse gases (Hoegh-Guldberg et al., 2018). For example, once carbon dioxide is added to the atmosphere, it persists for a long time, between 300 and 1,000 years, meaning its warming is nearly irreversible for a significant period (NASA, 2019). Similarly, two-thirds of the calculated warming caused by Nitrous Oxide ($N_2O$) is still present 114 years after emissions are halted (Solomon et al., 2010). Therefore, mitigation is unlikely to address the current and near future impacts of climate change and it is thus imperative to start planning for how to adapt to these impacts (Susskind, 2010).

Despite the importance of adaptation (and the legal obligations of countries under Article 7 of the Paris Agreement), it has historically been overshadowed by mitigation. Much of the attention and action on climate change globally over the past decade, has centred around climate mitigation, be that litigation, legislation or funding (Kuyper & Schroeder, 2018; Nachmany et al., 2017). For instance, in relation to funding and finance, mitigation finance accounted for 93% of global flows in 2017/18, with adaptation finance accounting for only 5% of the other flows (and finance for both mitigation and adaptation benefits was 2% of total flows) (Buchner et al., 2019).

Laukkonen et al. (2009) and Tol (2005) suggest the bias towards mitigation can be attributed to: (i) the extent to which mitigation can reduce impacts to climate-sensitive systems globally; (ii) the evidence and certainty surrounding the long-term benefits of mitigation; and (iii) the ability to measure and quantify emissions reductions. This is in comparison to adaptation which is typically more localised and less quantifiable

(Hallegatte & Corfee-Morlot, 2011; Klein, 2003). Despite the increasing recognition of adaptation in academic research globally, as demonstrated by Einecker and Kirby (2020) in their bibliometric study which showed a growth of publications, there has been less progress made on climate adaptation in practice in the UK[9] (Policy Connect, 2021). As such, the remainder of this chapter, and indeed this thesis, focuses specifically on climate adaptation.

## 2.3 Climate adaptation

In it its broadest sense, adaptation refers to an individual or system's ability to adjust in relation to their changing environment. The term is not new. In the 19th century, Charles Darwin used the term adaptation in relation to how organisms alter to become more suited to their environment (Thomsen et al., 2012). In addition to the natural sciences, socialist scientists (such as historians, anthropologists, and archaeologists) propose that adaptation is also a social phenomenon. An example being how societies and cultures have been able to survive historically, due to their ability to alter cultural practices (O'Brien & Holland, 1992).  Both perspectives (natural and social sciences) typically view adaptation as advantageous, with the changes to cultural practices in human societies being synonymous with the evolution of genetic traits in the natural environment (Orlove, 2009).

The concept of adaptation has been applied in a range of fields including ecology (Lenski, 2017; Turcotte et al., 2012), biology (Kauffman, 1991; McDougald et al., 1998), anthropology (Harpending & Sobus, 1987), and natural hazards and risk management (Burton et al., 1978; Solecki et al., 2011). It is only relatively recently, however, that the term has been applied in the climate discourse. Climate adaptation research and policy making began concurrently with increasing awareness of climate change from the late 1990s, however as discussed these activities were overshadowed by those focused on mitigation (Smit & Wandel, 2006).

[9] Policy Connect's Climate Policy Dashboard gives the UK's Adaptation Sector a score of 4/10 as they suggest the UK does not have sufficient policy frameworks for adaptation and lack measurable targets to assess progress against climate risk (Policy Connect, 2021).

There is no one singular definition of adaptation. This is due to differences in scale (such as community, city or system), areas of focus (e.g., water, agriculture or built environment) and audience (e.g., community, public or private sector) of the adaptation in question. Several of the most commonly referenced definitions of adaptation in relation to climate change are presented in Table 2.1. The differences in the definitions stem from evolving interpretations (i.e., if adaptation is an action or process), the aims and actors involved. All of the definitions do have a commonality in that they focus on adjustment of a system or culture in response to a stimulus; however the variety also suggests divergences in conceptualisation, interpretation and implementation of the term (Smit et al., 2000).

For the purpose of this thesis, when the term adaptation is used, it refers to the IPCC definition which is: “the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects” (IPCC 2014e, p.1758). This definition was chosen as it is the definition that governments and stakeholders in this research context most widely use. In addition, this definition contains the core components of alternative definitions (listed in Table 2.1) including the temporal element of adaptation addressing both current and future climate, the fact that adaptation can both mitigate risk and take advantage of opportunities and that these activities cut across both natural and human systems.

*Table 2.1: Summary of definitions of adaptation cited in the literature to show the breadth in nuance of interpretation, with the general meaning of altering practices and systems to reduce risk and/or grasp opportunity*

| | |
|---|---|
| Definition One | The IPCC (IPCC, 2014b, p.1758) defines adaptation as: “the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects”. |
| Definition Two | “adjustments in ecological-social-economic systems in response to actual or expected climatic stimuli, their effects or impacts” (Smit et al., 2000, p.225) |
| Definition Three | “Adaptation in the context of human dimensions of global change usually refers to a process, action or outcome in a system (household, community, group, sector, region, country) in order for the system to better cope with, manage or adjust to some changing condition, stress, hazard, risk or opportunity” (Smit and Wandel 2006, p.282) |
| Definition Four | “adjustments in a system’s behaviour and characteristics that enhance its ability to cope with external stresses” (Brooks, 2003b, p.8) |
| Definition Five | [process] ‘‘one by which groups of people add new and improved methods of coping with the environment to their cultural repertoire’’ (O’Brien & Holland, 1992, p. 37) |
| Definition Six | “actions that people take in response to, or in anticipation of, projected or actual changes in climate, to reduce adverse impacts or take advantage of the opportunities posed by climate change” (Tompkins & Adger, 2004, p.5) |
| Definition Seven | “Adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting non climatic changes. Adaptation strategies and actions can range from short-term coping to longer-term, deeper trans- formations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities.” (Moser & Ekstrom, 2010b, p.22026) |
| Definition Eight | “The process through which an actor is able to reflect upon and enact change in root and proximate causes of risk.” (Pelling, 2011, p.21) |

The following section (Section 2.4) introduces different theoretical interpretations of adaptation. The theoretical interpretations will be later explored in practice in Chapter 6. The conceptual diversity of adaptation illustrated also highlights the complexity of the topic, which is further explored in Chapter 3 in relation to decision-making.

## 2.4 Elements of adaptation and associated typologies

One of the biggest challenges associated with adaptation is that a one-size-fits-all approach is not feasible since the process of adaptation is inherently local (Hansen & Bi, 2017). The different elements and typologies (classification of types) of adaptation presented have been identified through a literature review, namely from the contributions of Biagini et al. (2014), Bosello et al. (2011); Fankhauser et al., (1999); Klein and Tol (1997) and Smit et al., (1999). A search for academic articles using the key word ‘climate adaptation’ was undertaken using Web of Science. The literature review scope pertained to adaptation theory, as such only papers which explored conceptual interpretations of adaptation are included here.

Several elements need to be considered when planning and implementing adaptation in practice. These elements include: (i) purposefulness; (ii) timing; (iii) scale; (iv) function; and (v) ambition as outlined in Table 2.2. Within these elements, there are different typologies. Typology in this case, denotes the different conceptualisations and approaches of the element, for example within timing, adaptation may be either responsive or anticipatory.

These elements of adaptation are described in the remainder of this section to provide necessary background to the reader on the topic of adaptation. In addition, this section aims to illustrate the diverse nature and complexity of adaptation. These elements are presented as they all interact with adaptation decision-making, aims, ambitions and activities. The range of different elements and typologies illustrates that the task of operationalising adaptation is incredibly challenging. It is therefore important to understand the multi-faceted nature of adaptation as both a theoretical concept and practical approach. As such, the remainder of this section describes each element and its associated typologies. Further reference to these elements and typologies is offered within the findings chapters (Chapters 6, 8 and 9).

*Table 2.2: Different Elements and Typologies of Adaptation. The arrow symbol denotes that there is a spectrum of types of adaptation.*

| **Elements of adaptation** | **Types of Adaptation (Examples of Terms Used)** | | **Reference** |
|---|---|---|---|
| Purposefulness: if adaptation occurs naturally or as a result of intervention | Autonomous ⟷ Planned<br>Spontaneous ⟷ Purposeful<br>Natural ⟷ Policy<br>Passive ⟷ Active | | (Smit et al., 1999) |
| Timing: when adaptation occurs (in relation to climate events) | Anticipatory ⟷ Responsive<br>Proactive ⟷ Reactive<br>Ex ante ⟷ Ex post | | (Smit et al., 1999) |
| Scale: the boundary of intervention | Individual, Population, Strategic | | (Smit et al., 2000) |
| Function: how adaptation is being achieved in practice | Building Adaptive Capacity | Research | (Füssel 2007a; Smit & Wandel 2006; UKCIP 2003) |
| | | Educate & inform | |
| | | Encourage behaviour change | |
| | Taking Action | Protect | |
| | | Accommodate | |
| | | Retreat | |
| | | Modify the threat | |
| Ambition: the change aspired to through adaptation | Incremental, Transformational, Resilient | | (IPCC, 2014c;Pelling et al., 2015) |

### 2.4.1 Purposefulness

A key element of adaptation is the extent to which it will happen naturally, or if it needs to be purposive, in other words, done with purpose or intervention. There are several different types of purposefulness discussed in the literature (as outlined in Table 2.2). There is autonomous adaptations (otherwise referred to as spontaneous, passive or natural) which take place in systems naturally (Smit et al., 2000). Adaptation may be autonomous or passive when a system responds to a climate impact spontaneously or automatically (Feenstra et al., 1998). Examples include shifts in ecosystem distributions as a result of a changing physical environment (IPCC, 2007).

Conversely adaptation may result from interventions, which are often referred to as purposeful, planned, policy or active adaptation (Smit et al., 2000). Examples of planned adaptation include constructing flood walls or developing early warning systems (Smit et al., 2000). Due to the purposive nature, planned adaptation relies upon decision-making processes. Therefore, in the case of deliberate, active decisions, a formal decision-making process or framework is required (Feenstra et al., 1998; IPCC, 2014). Purposeful or planned adaptation uses information about both the present and future climate to consider how future climatic and non-climatic conditions will differ from those previous experienced, how these changes impact the decision at hand and when action needs to be taken to address any risk (Fussel, 2007).

This thesis focuses on planned adaptation. The reason for this is two-fold. Firstly, the research focuses on decision-making processes and practices, thus necessitating a planned framing. Secondly, autonomous adaptation is unable to deliver the levels of adaptation required to deal sufficiently with the effects of climate change and thus cities must plan to take adaptation action (Dodman & Carmin, 2011). Planned adaptation is also the type most often associated with cities adapting through choices of local government. This type of adaptation is the focus of this research and will be explored further in the findings chapter of this thesis.

### 2.4.2 Timing

Another element of adaptation to consider is timing. Adaptation actions can be distinguished in terms of whether they are reactive or anticipatory in nature. Reactive or ex-post adaptation is the response to climate impacts once they have occurred whereas, anticipatory or proactive (ex-ante) adaptation is where action is taken in advance of climate impacts occurring (UKCIP, 2003).

Klein (2003) describes the different approaches (anticipatory or reactive) in practice. Examples of anticipatory adaptation action for human systems include early warning systems, purchase of insurance, construction of houses on stilts or raised from possible flooding. Reactive adaptation actions, on the other hand, may include compensatory payments, enforcement of new building codes or beach nourishment (Klein, 2003). Whether the action is anticipatory or reactive will influence how and why decisions are made. For example, reactive action may use evidence of local climate impacts to guide decision-making, whereas anticipatory action is more likely to rely upon climate projections and models. This thesis presents research on adaptation decision-making which places greater emphasis on anticipatory adaptation, given that Chapter 6 studies the development of a climate adaptation strategy.

### 2.4.3 Function

Adaptation seeks adjustments in different natural, social and economic systems, and as such the scope of function is wide. Adaptation actions are typically classified by two functions (or type of activity): (i) building adaptive capacity; or (ii) taking action on the ground. Building adaptive capacity relates to improving understanding of climate change and associated risk and impacts as well as enhancing institutional capacity; whereas action ‘on the ground’ refers to adaptation interventions which reduce risk or take advantage of any benefits (UKCIP, 2007). Each approach is described below and examples of different functions or intended effects are provided and summarised in Table 2.2. Whilst these terms are distinct in terms of type of activities, they are often intertwined as building capacity enables action on the ground and action on the ground develops knowledge to build capacity. It is necessary to achieve both immediate adaptation through delivery on the ground, as well as building future adaptive capacity by developing skills and knowledge to take action  (Doberstein et al., 2019; Thomsen et al., 2012; UKCIP, 2003).

#### *2.4.3.1 Building Adaptive Capacity*

Adaptive capacity is the ability of a social or environmental system to adapt to the impacts of climate change. Adaptive Capacity is defined by the IPCC (2014a, p.118) as the “ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences”.

Adaptive capacity of individuals is influenced by local conditions such as the presence of social networks, or access to financial, technological and information resources. It is also influenced by wider socio-economic and political pressures (Smit & Wandel, 2006). Adaptive capacity can differ significantly between communities, populations and regions. As such consideration of local conditions and context are needed to tailor adaptation interventions that aim to enhance adaptive capacity (Hansen & Bi, 2017).

The process of building adaptive capacity aims to enhance or strengthen a system’s ability to respond to climate change (Engle, 2011). Identifying barriers to adaptive capacity, such as limited financial or information resources, and providing support and assistance to address these needs is crucial. Adaptive capacity can also be improved through capacity building activities such as research and education. For instance, the process of adaptation can be advanced by research into new technologies and new methods of adaptation. In addition, adaptive capacity can be strengthened through the dissemination of knowledge through educational and public information campaigns, leading to behavioural change. Diverse capacity building mechanisms to strengthen adaptive capacity help build the knowledge, understanding and capability to implement adaptation actions (UKCIP, 2007)., To build understanding and capacity for climate adaptation, an array of capacity building activities and technical interventions are needed. This research was interested in both functions, building adaptive capacity and on the ground delivery, as both were explored in adaptation strategy development decision-making processes studied.

#### *2.4.3.2 On the Ground Delivery*

On the ground delivery of adaptation relates to taking action to live with the effects of a changing climate including both observed and expected gradual changes and extremes (Berrang-Ford et al., 2015; Ford & King, 2015; Hunt & Watkiss, 2011a). In addition, on the ground actions provide direct benefits to social and ecological systems by reducing their sensitivity and increasing their adaptive capacity (Füssel, 2007). On the ground adaptation can protect vital societal systems such as utilities as well as specific places. For instance, example adaptation actions include physical infrastructure such as flood defences, sea walls, or sustainable urban drainage systems warning through to early warning or observation systems (Biagini et al., 2014). On the ground action can be achieved through a number of approaches, including protecting, accommodating or retreating (Doberstein et al., 2019). In addition, alternative approaches include changing practices[10] or changing locations[11].

[10] Where the threat of climate change makes the continuation of an economic activity impossible or extremely risky, consideration can be given to changing practices. For example, a farmer may choose to substitute a more drought-tolerant crop or switch to varieties with lower moisture. Similarly, crop land may be returned to pasture or forest, or other uses may be found such as recreation, wildlife refuges, or national parks. Other example actions include installing green infrastructure or retrofitting buildings to prepare for the effects of floods and heatwaves (Biagini et al., 2014).

[11] Another adaptation response is that of retreat or changing location (Doberstein et al., 2019). Changing the location of economic activities may be required (Thomsen et al., 2012). There is considerable speculation, for example, about relocating major crops and farming regions away from areas of increased aridity and heat to areas that are currently cooler, and which may become more attractive for some crops in the future (Rosenzweig and Parry, 1994).

### 2.4.4 Level of Ambition

Adaptation plans can also differ in relation to their level of ambition (or change aspired to), which may be either be incremental or transformational. Incremental adaptation is defined as "actions where the central aim is to maintain the essence and integrity of a system or process at a given scale" (IPCC, 2014a, p.40). Transformational adaptation is defined as "adaptation that changes the fundamental attributes of a system in response to climate and its effects" (IPCC, 2014a, p.40). For example in relation to flooding, an incremental adaptation approach may be reinforcing existing dykes whereas a transformational approach is something such as the Thames Estuary 2100 plan which is an engineered barrier which can be raised or lowered to protect London from flooding, high tides and storm surges for the long-term future (Kates et al., 2012).

Pelling et al., (2015) suggest that transformation broadens the options for adaptation from actions to preserve systems and minimise drivers of vulnerability to activities that challenge the structure and function of current systems. Incremental adjustments which achieve short term wins but do not address rooted vulnerabilities or enable systemic change may delay transformation and enhance risk in the system (Pelling et al., 2015). Transformational adaptation which alters the fundamental attributes of systems and may be required to address the root causes of vulnerability however is highly likely to be conceptualized as political and contested (Eriksen et al., 2015). The type of adaptation is dependent on local context, needs and resource availability. Both incremental and transformational approaches are required in practice. This research was thus interested in exploring both types, however a prevalence for incremental adaptation was observed in the study (discussed in Section 6.4).

### 2.4.5 Scale

When considering adaptation actions, it is essential to identify the boundaries of the natural or social system being adapted, and thus the scale of the intervention required (Smit et al., 2000). Climate adaptation action may be considered at various levels or scales including geographic, sectoral and strategic (Klein & Tol, 1997). Geographic scales, for example, range from household, neighbourhood and regional adaptation actions. Sectoral interventions, conversely, may not be bound by location but instead a thematic or business interest area. Adaptation actions, whilst implemented typically at a local scale, can be influenced by drivers at the national and international scales such as legislation. As such, strategic adaptation is influenced by national priorities and synergies with other policy areas (Russel et al., 2020).

Although adaptation may be done at geographic, sectoral or strategic scales, multi-level action and coordination is ultimately required. There is a need for adaptation at the local level such as installing sustainable urban drainage systems in new developments through to the strategic level mainstreaming adaptation across the development and implementation of all policies (Patwardhan et al., 2009). Alignment and knowledge-exchange between actions occurring at multiple scales is therefore required for effective adaptation (Landauer et al., 2019).

The localised experience of climate impacts means a global legal response would not be sufficient enough and instead there are necessary roles and responsibilities at the national, regional and local levels for both mitigation and adaptation (Craig, 2010). Adaptation planning is often associated with action at the local level (Measham et al., 2011). This is in part due to the local nature of climate impacts, the unique way in which various regions will experience climate change and thus have different response needs and in particular the way in which local socio-economic and demographic characteristics influence local vulnerability, sensitivity and adaptive capacity (Hansen & Bi, 2017). Due to the increasing importance of local and city scale adaptation, this thesis seeks to understand the challenges associated with developing adaptation actions at these scales (as discussed further in Section 2.5).

#### 2.4.6 Reflections on typologies

Whilst climate change is a global challenge, it’s impacts will be experienced in varying ways across local, regional, national and international scales, resulting in different adaptation responses (Adger et al., 2005). The previous sections (Sections 2.4.1-2.4.5) introduced the concept of climate adaptation, outlined the different elements of adaptation and detailed the respective typologies of adaptation actions. This thesis is interested in climate adaptation. It must be noted, however, that climate adaptation is also often and increasingly referred to as climate resilience (Leichenko, 2011).

Leggett (2021, p.1) states, “grammatically, adaptation is a process, action, or sometimes the result of the action, whereas resilience is a condition or capacity. In practice, the distinctions and relationship between the two terms are more complicated, with numerous definitions used for each.” There are nuances in the interpretations of the terms. For instance, adaptation relates to adjustments within a system given long-term anticipated changes in the climate (Adger et al., 2005; Klein, 2003), whereas resilience can be conceptualised as withstanding a hazard in order to ‘bounce back’ to pre-disturbance conditions (da Silva et al., 2012a; Gunderson, 2016; Holling, 1973). Secondly, adaptation involves minimising negative impacts as well as taking advantage of any benefits of a changing climate, where resilience less explicitly acknowledges taking such advantages (Leggett, 2021).

Within this thesis, the terms climate resilience and adaptation are used interchangeably due to both terms being used synonymously within the research setting (introduced in Section 4.3.2). A differentiation is made when referring to ‘resilience’ in a more holistic sense, when not focused on climate change (as was the case in the Glasgow Resilience Strategy described in Section 6.1). A literature review on resilience is not offered here given the predefined scope. Relevant reviews of resilience are available in Kythreotis & Bristow (2016), Meerow et al. (2016) and McEvoy et al. (2013).

Resilience has also come to prominence in the form of ‘urban resilience’ (Friend & Moench, 2013; Leichenko, 2011; Tyler et al., 2016). This may be driven by increasing awareness, in literature and policy arenas, of the benefits and needs of using cities as effective scale for adaptation practice (Bulkeley, 2013; Castán Broto & Bulkeley, 2013; Hunt & Watkiss, 2011b). This thesis, through action research with Glasgow City Council, studied planned, anticipatory, city scale adaptation which sought to build adaptive capacity and take on the ground action to achieve incremental adaptation. Section 2.5 introduces the importance of cities for climate adaptation.

## 2.5 The importance of city level climate adaptation

Cities are often considered by policy makers as the engines for economic growth and cultural evolution. However, as dense, and interconnected hubs of human and economic activity predominantly located in coastal and flood plain regions, they are also vulnerable to climate change. The responsibility of planning for and adapting to these climate impacts lay largely with city governments (Carter et al., 2015; Cimato & Mullan, 2010).

Given that more than half the global population lives in an urban setting and this is expected to rise to 70% by 2050 (C40 Cities & UCCRN, 2018), it is critical to understand how best city governments can undertake climate adaptation. The importance of city-level adaptation has been highlighted for a number of reasons, including that cities: (i) are increasing in population (C40 Cities & UCCRN, 2018); (ii) are exposed and vulnerable to climate impacts (Hallegatte & Corfee-Morlot, 2011); but also (iii) have agency in the fight against climate change (Carter et al., 2015; Gencer, 2013; Rosenzweig et al., 2010). Section 2.5 expands on each of these three points and demonstrates the importance of city level climate adaptation.

### 2.5.1 Rapid global urbanization

Cities are steadily increasing in size globally as currently 67 million people are moving to urban areas annually (C40 Cities & UCCRN, 2018). It is predicted that by the year 2030, 60% of the global population will live in cities. This rapid urban growth can create challenges on legacy infrastructure such as sewers, energy, or water supply. Climate change adds additional stresses on these systems via direct and indirect climate impacts (as highlighted in Table 2.3)  (da Silva et al.,2012; Wilbanks & Fernandez 2014). Thus, it is important to understand climate adaptation in cities to safeguard and enhance the resilience of the majority of the world’s population.

### 2.5.2 Cities are vulnerable to climate impacts

Climate change will lead to a wide array of impacts on societies, economies and ecosystems globally (IPCC, 2014c). According to the C40 Cities[12] and the Urban Climate Change Research Network (UCCRN) (2018) 70% of all cities worldwide are currently experiencing the effects of climate change and nearly all cities are at risk of climate change, from both direct and indirect impacts.

---

[12] C40 is a network of the world’s megacities committed to addressing climate change. C40 supports cities to collaborate effectively, share knowledge and drive action (C40 Cities, 2021).

Direct impacts refer to both shocks from sudden events such as storms as well as stresses or gradual events like sea level rise (Hunt & Watkiss, 2011a). Over 90% of all urban areas in the world are coastal meaning direct impacts may arise from enhanced risk of flooding from storms and sea level rise (C40 Cities and UCCRN 2018). Indirect impacts are the consequences of direct impacts indirectly affecting transport networks, power, potable water supply, food distribution networks, waste management facilities and telecommunication systems (da Silva et al., 2012). Cities are often exposed due to their underlying geography; however, they are also vulnerable due to a range of other factors related to urban design and planning as well as the interdependent nature of urban systems.

Urban design can enhance climate risks in cities (Bulkeley, 2013). For example, impervious hard surfaces used within cities can reduce infiltration, accelerate runoff, and therefore increase risks of flooding (Carter et al., 2015b; Chen et al., 2016). Urban design can also create micro-climates which affects variables including temperature and wind. The urban heat island effect, for example, is where urban centres may be warmer than surrounding areas because of the structure of buildings, heat and carbon emissions of human activity and the replacement of vegetated surfaces with impervious built surfaces (Carter et al., 2015b).

There is often a connected nature of urban systems within a city. Cities have closely located and often interdependent infrastructure systems which mean that an impact on one can lead to cascading impacts effecting other systems (Bulkeley, 2013; Wilbanks & Fernandez, 2014). Table 2.3 identifies climate impacts (both direct and indirect impacts) that may be relevant for urban areas, including: (i) sea level rise on coastal cities, (ii) extreme events and their effects on built environment, (iii) effects on health because of increasing temperatures and extreme events, and (iv) effects on water availability and resources.

*Table 2.3: Examples of direct and indirect climate impacts in cities. Source Hunt and Watkiss (2011)*

| Climate Risks | Examples of direct impacts in cities | Examples of indirect impacts for cities |
|---|---|---|
| Sea-level rise | • Inundation and displacement of population<br>• Coastal flooding and storm surges<br>• Coastal erosion and loss of land<br>• Rising water tables and drainage problems<br>• Increased salinity of coastal environments<br>• Economic and leisure activities | • Changing dynamics of ecosystems<br>• Changes to use of coastal zone<br>• Risks to marine economies |
| Extreme events | • Damage to infrastructure systems, property, livelihoods and life from windstorms, flood events, heatwaves, and droughts | • Risks to economic production chains<br>• Risks to urban food supplies |
| Health | • Physiological effects of heatwaves and cold<br>• Changes in incidence of vector borne diseases<br>• Physical and mental health impacts of extreme events | • Risks to wider systems of health care and support |
| Water availability | • Reduced precipitation and groundwater recharging limits water availability<br>• Retreat of glaciers reduces urban water supplies<br>• Increased demand for water as temperatures increase<br>• Reduction in water quality as river flow decreases | • Risks to economic production chains<br>• Risks to urban food supplies |

### 2.5.3 The importance of city governments as agents for adaptation

The previous sections (Section 2.5.1 and Section 2.5.2) illustrated that cities are increasing in population and that cities already experience and will continue to be affected by climate impacts. There is a need to respond to such climate impacts. Therefore, city governments, being the primary form  will have a key role to play in climate adaptation (Bulkeley, 2010; Carter et al., 2015a; Cimato & Mullan, 2010). This Section 2.5.3 explores the responsibility of city governments for adaptation.

Local variations in climate impacts necessitate a local level response to adaptation. Adaptation discourse often places greater emphasis on the local consequences of climate change with a particular increasing recognition of the importance of the role of local authorities (Baker et al., 2012). This implies that city governments can and must play a significant role in managing the impacts of current and future climate change.

Local (or city) governments are also often responsible for vital services for citizens and businesses in their defined geographic area. These range from social care, schools, housing and planning to business support and pest control. In addition, local authorities are often the main delivery vehicle of anticipatory and planned adaptation and play an important role in addressing climate impacts and enhancing local climate resilience (Hunt & Watkiss, 2011c). The capacity of city councils in adapting to climate change also arises from their authority over local planning, land-use management, strategic decision-making and service deliver across a range of portfolios and their role in brokering relationships amongst actors (Measham et al., 2011).

There is an increasing transfer of powers from national and international legislation delegating responsibilities to local governments to implement adaptation measures (Baker et al., 2012; Hackenbruch et al., 2017). Continued urbanisation combined with alterations to urban scale governance for example may alter the previous dominance of the nation state, leading to greater powers being devolved to cities (Waite et al., 2013). Furthermore, city governments such as councils and city leaders are well placed to address climate change as they can be more easily held account by their citizens to make appropriate decisions, as opposed to international bodies (C40 Cities and UCCRN 2018).

City level climate change planning actually accelerated from the mid to late 1990s with a number of supporting organisations established at that time including ICLEI- Local Governments for Sustainability, Covenant of Mayors and C40 all with the intention to support governments to develop climate action plans (Biagini et al., 2014; Lee, 2013). Examples of how cities have demonstrated commitment to climate change adaptation include London's Climate Change Adaptation Strategy (Greater London Authority, 2011), Rotterdam's 'Climate Proof' adaptation programme (Rotterdam Climate Initiative, 2013) and the New York City Panel on Climate Change (New York City Panel on Climate Change, 2019; New York City Panel on Climate Change, 2010; Rosenzweig & Solecki 2010). It is evident that cities are increasingly become the focus point for climate adaptation actions and achieving international climate targets like the Paris Climate Agreement (Watts, 2017).

As powers and responsibilities to take adaptation action grow, cities will increasingly require guidance and methods to support them in adaptation decision-making, planning and implementation (Siders & Pierce, 2021; van de Ven et al., 2016). It will be vital that resources are appropriate for the context in which they are undertaken, being cognisant of the time and money available. In addition, the decision-making process and any decision support used within the process, will need to consider the knowledge and experience of those involved in decision-making (Palutikof et al., 2019).

Climate change and climate adaptation in cities is evidently a global topic. This thesis, however, focuses on climate adaptation occurring within Glasgow, Scotland, UK. Local (or city) councils are the most common type of local authority in the United Kingdom (Local Government Association, 2020). Councils are comprised of councillors who are elected by the public in local elections as well as permanent staff who perform duties to provide essential services to citizens. This thesis is concerned with the decision-making process of local councils and therefore local authority and city council will be used interchangeable, in reference to the local governance and decision-making body within a city. Section 2.6 explores current barriers and knowledge gaps to effective adaptation by city councils.

## 2.6 Knowledge gaps and barriers to effective city council led adaptation

City governments are increasingly becoming more aware of the need to adapt. Cities are actively enhancing their understanding of risks they face and planning adaptation actions to reduce these risks. Despite willingness to act, many cities will face unique barriers when attempting to undertake adaptation, such as limited political support, restrictive organisational cultures, short term priorities and competing interests (Ekstrom & Moser, 2014; Measham et al., 2011). Local government may also lack internal capacity and/or expertise required to understand and make decisions about climate change (Bierbaum et al., 2013; Nordgren et al., 2016).

As a result of such limitations, there has been a growing body of literature on ‘barriers’ to adaptation. Barriers that have been limiting climate adaptation in practice range from lack of financial resource (Hunt & Watkiss, 2011b), challenges in understanding climate science, lack of leadership (Amundsen et al., 2010; Bulkeley, 2010) and difficulty in selecting which of the many climate adaptation guidance resources and services are most appropriate (Stults et al., 2015). These barriers have been observed to restrict adaptation planning and implementation in San Francisco, California (Ekstrom & Moser, 2014), the Netherlands (Biesbroek et al., 2011) and French local authorities (Simonet & Leseur, 2019).

In recognition of these barriers, Rosenzweig and Horton (2013), Hunt and Watkiss (2011b) and Klein et al. (2017) stress the need for further study on how adaptation can be successfully undertaken at the city level. To address and overcome these barriers, there is an increasing array of tools, resources and services targeted at city governments to support climate adaptation. Despite the proliferation of these tools, there are limited empirical examples of how effective the tools are when implemented in practice and if they address needs of local adaptation practitioners (Nordgren et al., 2016). As such this research seeks to understand the decision-making landscape in-depth and assess the usefulness of different methods to support decision-making for climate adaptation in city councils. Decision-making processes and methods are explored in the following chapter (Chapter 3).

## 2.7 Conclusion

This chapter presented an overview of climate change and how it can be addressed through mitigation and adaptation. This chapter has demonstrated that climate change is happening with wide ranging consequences for all economic, social, and ecological systems. Whilst adaptation is key in preparing for these impacts it has been traditionally neglected in favour of mitigation. Nonetheless, adaptation is now receiving increasing attention. This chapter introduced adaptation and defined key concepts that will be used throughout the rest of this thesis. The knowledge gaps identified that are associated with city council led climate adaptation are further explored in Chapter 3 and were used to design the research objectives and methodology as outlined in Chapter 1. The next chapter introduces the subject of decision-making for climate adaptation, explores the emerging field of decision-making under uncertainty and presents an overview of different decision-making tools, approaches and support mechanisms that can be used to appraise adaptation options and enhance resilience.

# Chapter 3: Review of current approaches to city-level adaptation decision-making

> "The impacts of climate change are exacerbated by inefficient adaptation and mitigation decision-making, due to the complexity of the decision-making environment. As a consequence, there is no single approach to planning and decision-making. Climate change adaptation falls squarely in the domain of wicked problems that require collective learning and new modes of decision-making and collaboration."
>
> (Maani 2013, p. i)

Cities around the world must adapt to the changing climate. A key part of adaptation is the need to make complex decisions on how to invest limited resources in the most impactful way. As such, the decision-making process to appraise actions is of pivotal importance to the success of adaptation efforts (Orlove et al., 2020; Willows & Connell, 2003). Adaptation decision-support, according to Lourenco (2015, p.31), can be described as "the set of processes that create the necessary conditions for the production of decision-relevant information and its appropriate use". Effective decision support can aid decision-making by aiding the consideration of multiple alternatives, their trade-offs and how they contribute to identified goals (Jones et al., 2014).

Decision-making is the process of making choices (Edwards, 1954; Fulop, 2007). Humans undertake decision-making on a daily basis, ranging from simple choices such as 'should I take an umbrella?' through to more complex decisions such as 'should I change careers' or 'should I invest my savings' (Tsoukiàs, 2008). In the context of climate adaptation, the decision-making process affects how options are identified and evaluated as well as how the adaptation strategy is designed and conducted. There is a pressing need to understand how adaptation decisions are being made in practice, to better inform and improve both conceptualisation and recommended practice (Capela Lourenco, 2015).

This chapter introduces common conceptualisations and frameworks of the adaptation process in Section 3.1. Section 3.2 then discusses common characteristics of adaptation decision-making and a range of decision support methods available are introduced in Section 3.3. An assessment of the applicability of decision support methods to climate adaptation is offered in Section 3.4. Finally, knowledge gaps are presented in Section 3.5 and chapter concluded in Section 3.6.

## 3.1 Adaptation Process

Climate adaptation often involves a process of developing and implementing strategies to prepare for climate change. An adaptation strategy relates to a general plan of action to prepare for the impacts of climate change and take advantage of any emerging opportunities (IPCC, 2014b; Ranger et al., 2010; UKCIP, 2007). Adaptation strategies typically aim to reduce vulnerability and enhance resilience and include a mix of policies and actions (Lim et al., 2004).

As Chapter 2 outlined, the local nature of climate impacts implies there is no one size fits all approach. Similarly, there is no single method for adaptation strategy making (Kithiia & Dowling, 2010). Climate adaptation guidance and literature, however, typically conceptualises adaptation as a process of steps within a cyclical and iterative framework (Füssel, 2007a; Moser & Ekstrom, 2010b). The most widely used and commonly cited adaptation approach, variations on the Adaptation Wizard, utilises a risk-based cyclical tool (Street et al., 2019; Willows & Connell, 2003), which will be further explored within this section.

In 2003, the UK Climate Impacts Programme (UKCIP)[13] released a conceptual, cyclical framework to support adaptation decision-making, called the UKCIP's Risk and Uncertainty in Decision-making Framework (Willows & Connell, 2003). This was a staged framework aimed to support decision-makers to identify and manage climate risks (in the face of uncertainty) (Willows & Connell, 2003). The framework was premised on common decision-making and risk principles and is presented in Figure 3.1 (Brown et al., 2011).

[13] UK government sponsored programme to support climate adaptation established in 1997

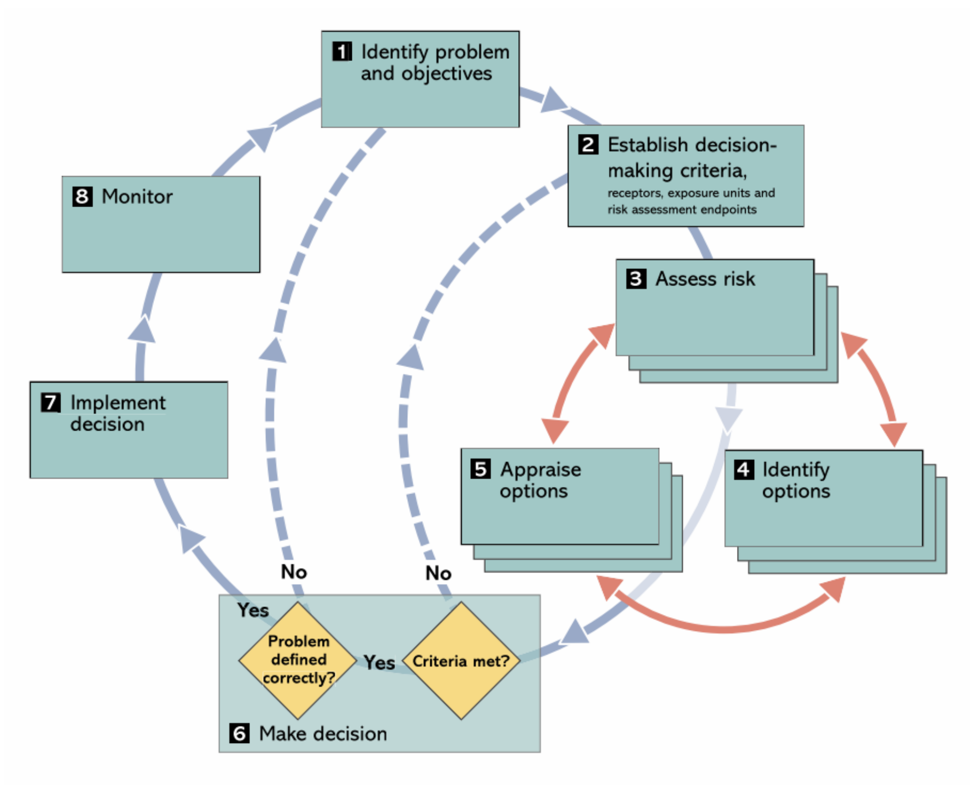



*Figure 3.1: UKCIP Risk and Uncertainty in Decision-making framework. Source Willows and Connell (2003)*

The theoretical Risk and Uncertainty in Decision-making framework was later transformed into an online support tool for adaptation practitioners, called 'The Adaptation Wizard'. According to Brown et al (2011), the Adaptation Wizard provided a 'light touch' version of the Risk, Uncertainty and Decision-making framework in response to criticism that it was overly technical and not in a user-friendly format. The Adaptation Wizard comprises a cyclical multi-stage process that guides users to undertake a series of steps as demonstrated in Figure 3.2. These stages are:

1. **Getting Started:** Identifying why the organisation is considering adaptation, define objectives, establish team
2. **Current vulnerability:** Assess how vulnerable an organisation is to the current climate, collate background information on how future climate change may affect the organisation and reflect on the organisation's previous response to experienced weather events
3. **Future climate variability:** Consider how the climate is expected to change, identify main climate impacts for sector or location of study, undertake a risk assessment
4. **Adaptation Options:** Identify a number of adaptation options, choose the most appropriate ones and create an implementation plan
5. **Monitor & Evaluate:** Assess implementation of selected options.

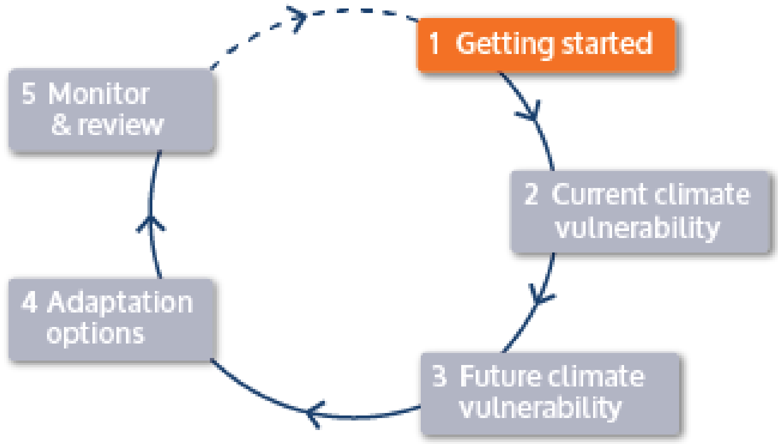



*Figure 3.2: The Adaptation Wizard (UKCIP, 2013). The solid line indicates the progression linearly from each step. The dashed line indicates that the process should be repeated regularly to ensure understanding is current and appropriate adaptation options selected accordingly.*

The Adaptation Wizard was one of the first adaptation tools of its kind. It acted as a catalyst and template for other countries to establish similar frameworks and initiatives. Examples include the German 'Klimalotse' (Umwelt Bundesamt, 2015), the Coastal Climate Adaptation Decision Support (C-CADS) tool in Australia (CoastAdapt, 2017) and the Scottish '5 Steps to Managing Your Climate Risks' Framework (Adaptation Scotland, 2009). The prevalence of the approach means that risk-based cyclical approaches to adaptation have dominated the way cities have undertaken climate adaptation strategy making (Clar & Steurer, 2018; Palutikof et al., 2019). The following section will introduce the concept of 'risk' in relation to climate adaptation.

### 3.1.1 Risk as a central component of adaptation cycle

The IPCC Fifth Assessment Report proposed that climate change can be viewed as a challenge of risk management (IPCC, 2014b; Jones et al., 2014). Risk management can occur via actions to reduce exposure or vulnerability. According to Jones et al., (2014) "risk management provides a useful framework for most climate change decision-making. Complex decision-making contexts will ideally apply a broad definition of risk, address and manage relevant perceived risks, and assess the risks of a broad range of plausible future outcomes and alternative risk management actions."

Risk based cyclical policy tools (such as the Adaptation Wizard) are one of the most commonly used to support climate adaptation (Clar & Steurer, 2018; Palutikof et al., 2019; Webb & Beh, 2013). Risk management, the process to assess risks with the intention to identify actions which reduce said risks, is central to the adaptation cycle. The cyclical process requires a series of sequential activities which are underpinned by a climate change risk assessment. These cyclical approaches are either centred on undertaking and responding to a risk assessment to achieve incremental change (Ranger, 2010) or focusing on striving for more transformational change (Park et al., 2012). Structured processes are often circular, recommending that the risk assessment is monitored and/or repeated if necessary (Palutikof et al., 2019).

Common interpretations of risk (across numerous fields) define it as the probability of the event multiplied by the consequences. Climate risk also follows this formula, however with nuances. There are multiple contributors to climate risk identified, including: (i) the hazard, the potential occurrence of a physical event which can cause damage; (ii) exposure or the presence of people or things which could be adverse affected; and (iii) vulnerability, or the propensity to be adversely affected by the hazard (Adger, 2006; Knopman & Lempert, 2016; Sharma & Ravindranath, 2019). Hazard, exposure and vulnerability can also each have associated probabilities and it is when they are combined together that they lead to the consequences that comprise risk (Knopman & Lempert, 2016). For adaptation planning, it is important to distinguish the different contributors of risk so as to be better able to improve them and adapt.

Climate adaptation prepares for and responds to risks associated with climate impacts. It is therefore necessary to understand what influences climate risk. Risk is a function of the climate or weather event (hazards) as well as the exposure and vulnerability to such hazards (Cardona et al., 2012). Effective adaptation requires a thorough understanding of the concepts of exposure and vulnerability, and their dynamics over time. This section, therefore, introduces the concept of risk and outlines key influences such as hazard, exposure and vulnerability as identified by the IPCC (2014e)[14]. Whilst this thesis focuses on options evaluation rather than risk assessment

[14] It is recognized that risk assessment in other fields typically involves calculation of consequence (the impacts that may occur) and likelihood. Within climate adaptation, however, it is acknowledged that the consequence of

*per se*, it is important to understand the underlying principles of risk when discussing climate adaptation and appraising options. The IPCC AR5 Working Group 2 surmised that "risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system and socioeconomic processes including adaptation and mitigation are drivers of hazards, exposure, and vulnerability" (Field et al., 2014, p.37). These concepts are illustrated in Figure 3.3 and definitions presented in Table 3.1.

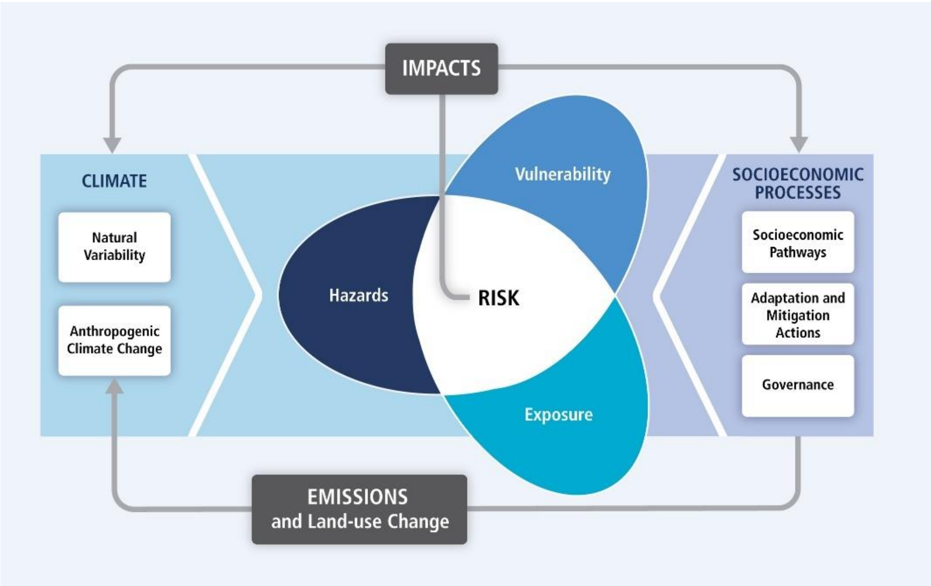



*Figure 3.3: Climate risk conceptualisation of IPCC AR5 WGII (Source: IPCC,2014)*

The severity of climate impacts is heavily influenced by the level of vulnerability and exposure to the hazard (Cardona et al., 2012). For example, in relation to flooding, there may be more adverse consequences if properties are exposed (i.e., within a flood plain) and the population are elderly, less mobile and have limited access to emergency services (or are more vulnerable). Vulnerability and exposure vary across areas as a result of economic, social, geographic, demographic, cultural, institutional and environmental factors (Cardona et al., 2012). Understanding vulnerability and exposure is a prerequisite for identifying and implementing appropriate adaptation solutions.

---

climate impacts are influenced by broader factors such as exposure, vulnerability and sensitivity. This nuance is captured in the inclusion of these concepts within risk conceptualization (IPCC, 2014d). Furthermore, the IPCC advise that the term risk should be used in reference to consequences for human or ecological systems and not when describing a change in frequency and/or magnitude of physical hazards (Reisinger et al., 2020).

*Table 3.1: Descriptions of hazard, exposure and vulnerability*

| **Term** | **Description** |
|---|---|
| Hazard | Hazard represents the possible occurrence of physical events that can adversely affect vulnerable or exposed elements (Cardona et al., 2012). A hazard is a component of risk and not the risk itself. Hazard is defined by the IPCC (2014a, p.124) as<br><br>"The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts."<br><br>Adaptation is considered in relation to climatic stimuli and over time these have been referred to as stresses, disturbances, events, and hazard. The stimuli for adaptation can be described as the climate or weather condition (e.g. increasing precipitation) or as the impacts of these climate conditions (e.g. flooding) (Smit et al., 2000) |
| Exposure | Exposure refers to what is in an area where a hazard may occur (Cardona et al., 2012). Exposure is defined by the IPCC (2014a, p.123) as:<br><br>"The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected."<br><br>Exposure is a determinant of risk, but not solely by itself. One can be exposed but not vulnerable. For example, houses built in a floodplain may have adaptation measures in place to not be affected by floods. |
| Vulnerability | Vulnerability is defined by the IPCC (2014a, p.128) as:<br><br>"the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt".<br><br>There is a broad field of literature on the interpretation of vulnerability including significant contributions such as Füssel (2007) and Smit & Wandel (2006). Vulnerability framing may suit when specific risks are identified and specific actions being considered whereas resilience framing may be more suitable to consider holistic range of impacts along with the interrelationships between them (Engle et al., 2014). Vulnerability is dependent on the hazard and impacts and relates to the effects or possible change of a system when experiencing a perturbation (Ing et al. 2006).<br><br>Vulnerability relates to the social construction of risk, or the idea that society through altering the physical world may create risks by transforming physical events into hazards through processes which enhance the exposure and vulnerability of certain groups of society (Wisner et al., 2004). Different conceptual frameworks and definitions of vulnerability exist and lead to varying responses to address causes of vulnerability (Brooks et al., 2005; Cutter et al., 2008; Füssel & Klein, 2006). The IPCC framework has evolved over time with the IPCC Fourth Assessment describing vulnerability as a function of exposure, sensitivity, and adaptive capacity. This is adopted by (Brooks, 2003b; Füssel, 2007; Füssel & Klein, 2006). This framing focuses on vulnerability to climate change and incorporates long-term trends and stresses rather than just current shocks. Across these interpretations, a lack of capacity to anticipate, cope with and recover from climate events and associated impacts is a causal factor of vulnerability (Cardona et al., 2012) |

### 3.1.2 Options identification and appraisal within adaptation cycle

A key step in the development of an adaptation strategy is the identification, assessment, prioritisation and selection of adaptation actions and measures to inform decision-making (Ranger, 2010; UKCIP, 2007; Willows & Connell 2003). Decisions will need to be made to reduce or manage anticipated climate risks (UKCIP, 2003b). Such decisions may relate to addressing problems where climate change is the primary concern and where climate change is only one of a number of factors influencing the decision. Within this thesis, adaptation decisions refer to both circumstances. Examples of climate related decisions faced by cities include adapting and upgrading aging infrastructure or coping with sea level rise (Knopman & Lempert, 2016).

The decision-making process can be aided via decision support. Decision support involves a diverse set of resources aimed at addressing complexity and supporting decision makers in improving their understanding to aid their evaluation of management options (Pyke et al., 2007). With more powers and responsibilities to take action on climate adaptation, cities will require frameworks and decision support to help them understand what they should do.

Within all adaptation strategy development and decision-making processes, a key step is the evaluation of adaptation options. As Park et al. (2012) state, “adaptation includes not only the set of actions undertaken to maintain the capacity to deal with current or future predicted change, it also relates to the decision-making process associated with change management itself” (p.115). This decision-making process and evaluation can be assisted by decision support.

Decision support typically consists of a structured decision-making process. Such a process aims to support decision makers in identifying the most suitable actions, consider when these should be implemented and develop a plan accordingly (Jones et al., 2014; National Research Council, 2009). According to Moser (2009, p.11) decision support for climate adaptation consists of “processes of interaction, including different forms of communication, potentially useful data sets or models, reports and training workshops, data ports and websites, engaging any level of governance, at any stage in the policy- or decision-making process”. Decision support is particularly useful for decision makers to help address the limitations of human reasoning and ensure decisions relate to the best available evidence (Morris, 2018).

Step-by-step decision-making processes typically include identifying a decision that is required to be made, collating information pertaining to it and assessing solutions, then selecting the optimum solution (Buchannan & O’Connell, 2006). The suggested steps for decision-making within the UKCIP Climate Risk Framework are illustrated by the inner circle in Figure 3.1 which is embedded within the wider loop of the framework. The outcome of the decision-making process is typically a quantitative appraisal of adaptation options (Ranger, 2010). The decision cycle has been widely adopted in climate adaptation, however not all of the stages within the cycle are commonly applied in practice (Mehryar et al., 2022). Within urban adaptation decision-making, the earlier decision-making steps (i.e. identify problem and establish decision-making criteria) focus on knowledge sharing and raising awareness, whilst the latter stages (i.e. evaluating, selecting and implementing adaptation options) are more focused on taking action (Surminski & Leck, 2017).

Options evaluation is included within the adaptation cycle, but exact methods to use or actions to undertake are not specified. There is limited information within guidance on how adaptation options should be identified and appraised. The IPCC AR6 report (Ch 17, p31 forthcoming in 2022) highlights this stating “few reports and peer-reviewed literature, have been available that document the actual experiences and outcomes of decision-making (the actual making and implementing of decisions), the contexts in which different methods and processes were tried, and an evaluation of the costs and benefits of the approaches. As a result, there are few analyses that compare the effectiveness of different decision practices in order to identify best practice for different contexts”. The process used is highly dependent on the context of application. As such, the following section (3.2) explores how the context surrounding adaptation decision-making influences the quality of decisions made.

### 3.2 The characteristics of climate adaptation decision-making

The previous section introduced a commonly used adaptation decision-making cycle and the importance of decision support. The selection and use of decision-support is dependent on the characteristics and context of the problem being addressed. Generalisable characteristics of climate adaptation decision-making include complexity, uncertainty, temporality and resource (Dessai & Hulme, 2004; Lourenco, 2015; Maani, 2013; Ranger et al., 2010). Each will be explored here.

Complexity is an important aspect of the decision-making context and influences which support tools are appropriate. Complexity arises from the interconnected nature of the climate with ecological, economic and social systems, as discussed in Section 2.1. Aspects of complexity which exist within adaptation decision-making include: trade-offs between options, either costs and benefits of beneficiaries or those who will suffer, the need to address and incorporate economic, social and environmental factors, inherent uncertainty throughout, predicting effectiveness and benefit of adaptation options, timescales and spatial scales (Catenacci & Giupponi 2009; da Silva et al., 2012; Vermeulen et al., 2013). To address these complexities, present in adaptation decision-making there is a need to: (i) incorporate economic, social and environmental factors in decision-making to explore the system as a whole; and (ii) understand trade-offs between stakeholders (either monetary or other) (Maani, 2013). Such actions to identify and address complexities, influences the selection of decision support tools.

Problem framing puts an emphasis on the problem definition. According to Bardwell (1991, p.603) “how one defines a problem determines one’s understanding of an approach to that problem, being able to redefine or frame a problem ant to explore the ‘problem space’ can help broaden the range of alternatives and solutions examined.” The choice of framing can therefore influence how the problem is understood and addressed and may be used to focus on a particular part of a broader complex problem.

Uncertainty is a second key characteristic of the climate adaptation decision-making context (Dessai & Hulme, 2004; Willows & Connell, 2003). Many other decision-making processes face similar challenges with regard to uncertainty, however climate adaptation is unique in the scale, speed and extent of adaptation that may be required and the need to consider and anticipate uncertain futures (Ranger, 2010). Uncertainty is the quality of knowledge held in relation to risk (Willows & Connell, 2003). There are different forms of uncertainty, including aleatory[15] and epistemic[16] (Ranger, 2010). Understanding what forms of uncertainty exist and the extent to which these matter to the decision-maker, should inform decision-support selection. As uncertainty is prevalent throughout the climate change adaptation process, from uncertainty surrounding climate impacts, climate projections, adaptation choices and effects of interventions, the ability to explicitly incorporate uncertainty into the decision-making process is another important factor in methods choice when a selecting decision support tool (Catenacci & Giupponi, 2009; Falloon et al., 2014).

Temporality is a third characteristic identified as important for climate adaptation (Baker et. al,  2018; Brace & Geoghegan 2011; Fincher et al., 2015). Adaptation decisions must be made, despite uncertainty existing (Kwakkel et al., 2016; Lempert, 2003). Adaptation decision-making should therefore consider if adaptation options are justified given the level of uncertainty regarding the future. The temporal connection between the present and the future of a specific place in relation to climate change may be poorly understood (Fincher et al., 2015). The collective vision of a future, however, can shape action in the present  (Baker et al., 2018). The need to address temporality is often employed using discounting of costs and benefits. This is a commonly used approach to make benefits and costs occurred through time comparable on a single monetary equivalent scale. Within the UK, this method is set out in the UK Treasury Green Book (HMT, 2022). Decision-support may be required to help consider the effect of taking adaptation actions now and how they may influence future outcomes. Thus, the timing of decisions and the extent to which these

[15] Aleatory uncertainty relates to variation and randomness within a system that can not  be reduced. An example of aleatory uncertainty in case of adaptation would be natural unpredictable differences in the climate system. Natural variability of the climate system leads to scientific uncertainty or incomplete understanding of climate projections and impacts (Bree & Sluijs, 2014; M Catenacci & Giupponi, 2009).  Estimating the probability of climate change is challenging and leads to divergences of opinion on its appropriateness within the adaptation community as highlighted by Dessai & Hulme (2004).

[16] Epistemic uncertainty relates to limited information or knowledge and can be addressed with further research. An example of epistemic uncertainty in relation to adaptation relates to human decisions that affect climate change. Gaining knowledge through climate projections, modelling climate impacts or assessing benefits of alternative adaptation options can, to some extent, reduce epistemic uncertainty but not eliminate it (Catenacci & Giupponi, 2010; Morgan Granger & Henrion, 1990; Pollino et al., 2008).

are considered within decision-making processes will inform decision-support selection.

Lastly, resource availability is a characteristic affecting climate adaptation decision-making. Multiple studies have demonstrated that resource constraints, either limited financial resources, lack of information, or limited institutional capacity, can impeded adaptation options (Ford et al., 2011; Moser & Ekstrom, 2010b; Nalau et al., 2015). Therefore, decision-support selection should be cognisant of the potential resource limitations and how resource availability could change over time.

Such problems which are defined by complexity, uncertainty, long timescales and potential significant consequence, mean that it is challenging to collate enough certain information to make optimal adaptation decisions using common decision-making approaches (which seek to maximise utility) (Brown et al., 2011). These situations were identified as 'wicked problems' by Rittel and Webber (1973). Wicked problems are those which are challenging to scope, face difficulties in identifying causes due to complex nature and existing interdependencies and there is no sole solution to the problem (Rittel and Webber, 1973). Such occurrences are also described by Ravetz & Funtowicz (1991) as post-normal, since they challenge 'normal' decision-making. Wicked problems, like adaptation, necessitate an alternative approach to decision-making which acknowledges uncertainty.

Complexity, uncertainty, temporality, and resource availability all influence adaptation decision-making. Consideration of these characteristics should be made when selecting a decision support method for adaptation options evaluation. The following section (3.3) explores commonly available decision support methods and assess them in relation to the identified characteristics.

## 3.3 Evaluating decision support methods for climate adaptation

Decision-making for climate adaptation involves the process of identifying, appraising, selecting and implementing actions to prepare for and adapt to the impacts of both current and projected climate change (Jones et al., 2014; Ranger, 2010). Decision processes aim to help decision makers assess risks, costs and obligations proposed before making a choice (Morgan et al., 1990). A decision support tool or method can be used to support or facilitate decision-making (Palutikof et al., 2019). According to Jones et al. (2014) “decision support is situated at the intersection of data provision, expert knowledge, and human decision-making at a range of scales from the individual to the organization and institution. Decision support is defined as a set of processes intended to create the conditions for the production of decision-relevant information and its appropriate use.” In addition, decision support may be most effective when it is cognisant of the context in which it is being applied (Jones et al., 2014).

Decision support for adaptation can assist with problem framing, interpreting information, social learning, as well as prioritising, implementing and evaluating adaptation progress (Fünfgeld et al., 2019). There are a variety of methods available to assist with decision-making and options evaluation; however, the choice as to which method to use is dependent on a multitude of factors (Bowyer et al., 2015). Method selection should assess availability of data to be used within the evaluation and requirements of each tool. This includes availability of qualitative and quantitative data and spatiotemporal information. Other considerations should include stakeholder priorities, time and skills available to the decision maker and how these decisions fit within the wider adaptation decision cycle (Dittrich et al., 2016b). Therefore, key factors to consider when selecting a decision support methodology or tool include how it addresses complexity, incorporates uncertainty and time, as well as the resources, level of input, data and expertise required to use it.

Adaptation strategy development and options appraisal at the local level can be informed by various tools, methods, techniques and approaches, ranging from participatory engagement, expert-based approaches or computerised decision support systems (Watkiss & Hunt, 2013). Decision-making approaches which are used widely across climate policy making include cost-benefit analysis (Baer & Spash, 2008; Ryan & Stewart, 2017; Stewart et al., 2014), cost-effectiveness analysis (Metroeconomica, 2006; Skourtos et al., 2014) and multi-criteria analysis (Preston et al., 2013; Van Ierland et al., 2013), as well as scenario planning (Dessai et al., 2005; Dunford et al., 2014; Kok & Pedde, 2016; Star et al., 2016), causal loop diagrams and system dynamics (Sahin et al., 2013) and Bayesian Belief Networks (Catenacci &

Giupponi, 2009; Musango & Peter, 2007; Richards et al., 2013; Sperotto et al., 2017). The next section will provide an outline of these commonly used decision support methods and review their applicability to the climate adaptation characteristics identified in section 3.2. A summary of this high-level assessment is provided in Table 3.2.

*Table 3.2: Overview of Decision-Making methods and their ability to address complexity, uncertainty, temporality and resource challenges relating to climate adaptation decision-making. A check symbol indicates that the method addresses the factor, a cross indicates the method does not sufficiently address the factor for climate adaptation decision-making.*

| **Description of decision-making support method** | **Complexity** | **Uncertainty** | **Temporality** | **Resource & Level of Expertise Required** |
|---|---|---|---|---|
| **Cost Benefit Analysis** - CBAs focus on presenting the impacts of options in monetary terms so as to be compared across common unit and the steps involved include defining the decision, deciding upon decision criteria, estimating cost of actions, estimating benefits each would incur, weighing costs and benefits in relation to quantitative indicator, considering uncertainty and potential outcomes, applying criteria and making decision (Snell, 2011). | ✗ | ✓ | ✗ | Low |
| **Cost Effectiveness Analysis** - Cost effectiveness analysis (CEA) is an alternative to CBA where adaptation actions are assessed based on the relation between costs and benefits, but where benefits do not have to be measured in monetary terms (Watkiss & Hunt, 2013). This method works best in situations where benefits can all be measured in the same metric. | ✗ | ✓ | ✗ | Low |
| **Multi Criteria Analysis** - Multi-criteria analysis (MCA) is a method of decision analysis which enables decision makers to prioritise decisions based on assessing multiple criteria (which may be in monetary and non-monetary formats) in relation to desired outcome (Dodgson et al., 2009). | ✓ | ✓ | ✗ | Moderate |
| **System Dynamics** - System dynamics (SD) is another methodology for simulating complex systems to observe and simulate dynamic behaviour and to manage complex feedback systems (Pruyt, 2006). System dynamics aims to characterise complex, non-linear systems through examining interactions and feedback loops. SD often incorporates Causal Loop Modelling (CLM) which is a tool for mapping relationships within a complex system, to create a diagram which identifies linkages between various components, showing cause and effect relationships as well as feedback loops (Cavana & Maani, 2000). | ✓ | ✗ | ✓ | High |
| **Scenarios** - Scenarios are plausible possible future which allow one to envision and assess outcomes of possible decisions in different contexts (Moore et al., 2013). Scenarios describe current and future states and explicitly acknowledge uncertainty and this focus on uncertainty puts emphasis on need for best strategy process rather than simply the best strategy | ✓ | ✓ | ✓ | High |
| **Real Options Analysis** - Real Options Analysis (ROA) is a method which quantifies investment risk related to uncertain future outcomes. As an approach it considers the value of flexibility of investments in terms of timing of capital investment and ability to alter as the investment progresses and evolves (Buurman & Babovic, 2016). | ✓ | ✓ | ✓ | High |
| **Bayesian Belief Networks** - Bayesian Belief Networks are a modelling approach which uses probabilistic rather than deterministic relationships to describe and understand connections between variables within the system to provide likelihood of outcomes to inform decision-making (Catenacci & Giupponi, 2009). | ✓ | ✓ | ✓ | Moderate |

### 3.4 Assessment of decision support methods in relation to climate adaptation context

A decision support system may enable the management of uncertainties and assessment of various adaptation options. Traditional decision-making methods may have limitations when applied within the context of climate adaptation (Dittrich et al., 2016a). As such, the remainder of this section explains decision support methods and how they address the characteristics identified as important for climate adaptation decision-making. This section reflects on the methods outlined in Table 3.2 and appraises their relevance to climate adaptation decision-making.

Cost benefit analysis (CBA) and cost effectiveness analysis (CEA) are well-established methods; however they may be challenging to apply in the complex and uncertain problem area of climate change adaptation. This is due to the fact that while the costs of adaptation interventions may be quantifiable currently, the expected future benefits are often much more difficult to define and quantify. For example, in CBA, economic analysis is grounded in discounting, however due to the long-time scales of impacts of climate change, the ethical responsibilities to future generations is key to the problem, and the practice of discounting may disregard the wellbeing of future generations (Baer & Spash, 2008). In addition, CEA is well suited to situations where benefits of adaptation options can be compared via the same metric, and whilst this may be feasible in narrowly defined technical solutions this may not be the case for all adaptation interventions and minimises the potential for cross-sectoral use (Dittrich et al., 2016; Watkiss & Hunt, 2013). The publication of supplementary Green Book Guidance on ‘Accounting for the effects of Climate Change’ by the UK Government in 2020 provides guidance on how to use these methods more effectively for climate adaptation (Defra, 2020).

System dynamics models are commonly applied across sectors but have some limitations when applied to the climate adaptation context. For instance, a disadvantage of system dynamic models is that due to the simplicity of linking variables, which may result in models increasing rapidly in size and complexity beyond being useful, it obscures key structure or influential leverage points (Kelly (Letcher) et al., 2013). Causal loop maps (CLM) within system dynamic models offer value in that they can help visualise and map relationships between variables as well as illustrating direction of causality. A drawback, however, is that simplicity masks subtlety and it is difficult to understand dynamic behaviour from a causal-loop diagram (Richardson, 1986).

Lastly, scenarios can be used across several temporal horizons including short and long-term and incorporate views and interaction of diverse stakeholders to create shared understanding (Burt & van der Heijden, 2003). However, scenarios can be limited in their ability to integrate all the presumptions of projections and complex drivers to develop sufficiently different scenarios and have significant time and resource requirements (Moore et al., 2013). Scenarios are also typically qualitative, which may be an issue for situations where adaptation decision-makers request quantitative information.

All of the methods discussed in Section 3.4 so far, have limited potential for considering uncertainty, reducing their suitability to adaptation. As discussed, it is important to consider uncertainty during decision-making for climate adaptation as a result of considerable amounts of uncertainty associated with climate change projections, impacts and responses (Dessai & van der Sluijs, 2008). These circumstances make the above methods less suited to adaptation.

Real Options Analysis (ROA) is a method which quantifies investment risk related to uncertain future outcomes. As an approach it considers the value of flexibility of investments in terms of timing of capital investment and ability to alter as the investment progresses and evolves. This can help indicate when it is preferable to invest at that time or to wait (Watkiss et al., 2013). Real options analysis does not treat decisions as single decision but instead multiple decision-points and options (Siders & Pierce, 2021). In the adaptation context, ROA supports idea of iterative adaptive risk management as it has flexibility in timing and implementation of actions. In practice, it is often applied for investment analysis for major capital investment projects. There are challenges with applying ROA to climate adaptation decision-making due to the underpinning assumptions. For instance, ROA is unclear about value created and ROA requires expected values over a set of scenarios which may be difficult to obtain (Kwakkel, 2020). ROA may form part of a Cost Benefit Assessment.

Bayesian Belief Networks (BBNs) are a method that are used commonly in risk assessment and decision-making across sectors such as safety (Khakzad et al., 2011; Zarei et al., 2017), reliability modelling (Marquez et al., 2007; Sanford & Moosa, 2012; Weber & Jouffe, 2003), software quality (Dragicevic et al., 2017; Wagner, 2010) and healthcare (McLachlan et al., 2020; Stojadinovic & Felix, 2010). BBNs are increasingly recognised for their potential to climate adaptation (Catenacci and Giupponi, 2009; Richards et al., 2013; Sperotto et al., 2017). Catenacci and Giupponi (2009) argue that the features of Bayesian Networks have potential to characterise, incorporate and communicate uncertainty within climate adaptation, to provide efficient decision-making support. Given these reasons, and that BBNs could potentially address the limitations of other methods, this thesis explores the application of BBNs to climate adaptation specifically.

## 3.5 Identifying Bayesian Belief Networks as a method of interest for climate adaptation

Based on the discussion in Section 3.4 and the research setting and adaptation decision-making context (presented in Section 4.3 and Section 6.1 respectively), BBNs were identified as a method able to address the complexity, uncertainty and temporality associated with the climate adaptation context. It was also found that despite the potential of BBNs to the field of adaptation being highlighted Catenacci & Giupponi (2010) and Sperotto et al. (2017), there has been minimal use of the method to support climate adaptation decision-making to date. As such, it was decided to assess the value of BBNs to city-level climate adaptation decision-making (the results of the BBN study are presented in Chapter 8). This section introduces the method of BBNs and their application to climate adaptation to date. A description of the origins of BBNs and the components of a BBN is offered in Section 7.1 and Section 7.2

BBNs are widely used in complex and uncertain situations. For instance, BBNs have been applied in the fields of healthcare (McLachlan et al., 2020; Stojadinovic & Felix, 2010), safety (Khakzad et al., 2011; Zarei et al., 2017), reliability modelling (Marquez et al., 2007; Sanford & Moosa, 2012; Weber & Jouffe, 2003) and software quality (Dragicevic et al., 2017; Wagner, 2010). In recent years there has also been emerging use of BBNs within the climate adaptation field (de Nijs et al., 2014; Melorose et al., 2015; Molina et al., 2013). The use of BBNs within the field of climate adaptation, however, is limited despite their potential (Catenacci & Giupponi, 2010; Sperotto et al., 2017). Initial applications of BBNs within the climate adaptation context are presented in following paragraphs, in relation to their role supporting risk assessments, problem understanding, communication and options appraisal.

BBNs have been used to support climate change risk assessments. Sperotto et al (2017) explored the potential of using BBNs for climate risk assessment methods, identifying benefits such as the ability to assess multiple stresses or hazards within the same framework, ability to communicate uncertainty and the analysis of different scenarios. Specific examples of BBNs for climate change risk assessments include, Merritt et al. (2015) who combined hydrological and biophysical data with household livelihood indicators in a BBN to assess drought resilience and Lee et al's (2020) application of a BBN for a risk assessment of heatwave implications in South Korea. These studies were often top-down with limited involvement of stakeholders, which this thesis explored.

BBNs can be also applied to the problem understanding phase of climate adaptation. BBNs can be used to facilitate data sharing amongst stakeholders, to build consensus and enable public outreach (van Dongeren et al., 2014). Richards et al. (2013) for example, combined systems thinking and BBNs to develop and assess actions for climate adaptation in South Queensland, Australia. Participatory workshops developed a BBN to represent adaptive capacity perceived by stakeholders. BBNs can thus be used for options identification and appraisal for climate adaptation action. For instance, BBN were used to understand the impacts of interventions on climate change resilience relating to climate smart agriculture in Malawi by (de Nijs et al., 2015). Similarly Manson et al. (2002) and Maskrey et al. (2016) illustrated the utility of BBNs to support decision makers in assessing flood interventions in relation to identified objectives. This research builds on these earlier contributions and explores the application of BBNs within a local authority context, given the challenges arising from the context, content and process as described in Chapter 6.

Characteristics of BBNs, such as integration of multiple data sources, ability to update and their visual structure, lend themselves well to the field of climate adaptation decision-making. For example, studies of BBNs in climate adaptation to date highlight that since BBNs update probabilities based on new information, they may be very useful for adaptive management and well suited to the context of climate adaptation decision-making (Catenacci & Giupponi, 2010; Sperotto et al., 2017). Secondly, as BBNs are helpful in creating a structured framework in which different types and sources of knowledge can be integrated, this also makes them applicable for research on climate adaptation and resilience which incorporates various environmental, economic and social data (Lynam, 2016).

Limitations of previous BBN studies, however, include lack of stakeholder engagement, significant requirement of technical or specialist skills to construct and utilise the BBN and limited consideration given to decision-making setting or decision maker's available resource (Catenacci & Giupponi 2009; Sperotto et al., 2017; Uusitalo, 2007). Apart from the contribution of Richards et al. (2013) there has been limited critical assessment of the usability of BBNs for adaptation decision-making within a local authority. Despite theoretical advantages over the other methods with regards to helping adaptation decision makers deal with contextual characteristics, Sperotto et al. (2017, p.320) highlight that the application of BBNs in the context of climate change 'represent a limited explored field'. This research therefore seeks, through action research, to explore the value of BBNs within a local authority setting to support adaptation decision-making. More information describing the structure of BBNs is provided in Section 7.1 and how a BBN was used within this research in Chapter 8. The next section reflects on knowledge gaps pertaining to climate adaptation decision-making.

## 3.6 Climate adaptation decision-making knowledge gaps

An area that requires further study is how adaptation decisions are made in practice, specifically at the city level. This section reflects on knowledge gaps affecting climate adaptation decision-making specifically. Points of discussion follow on from consideration of knowledge gaps to city-level adaptation at the end of Chapter 2 in Section 2.6.

With increasing powers and responsibilities to take action on climate adaptation, city councils will require decision support to ensure appropriate adaptation is undertaken. Whilst numerous decision support tools, frameworks and methods are being developed in academic settings and via consultancies (Chapman, 2018; Umwelt Bundesamt, 2015; Willows & Connell, 2003), there is limited rigorous assessment of the practicalities of applying these approaches in real world settings (examples do include Clar and Steurer 2018; Palutikof et al., 2019; Street et al., 2019). Given that city level strategies are often the locale of action, it is also crucial to understand the associated challenges and limitations of building these strategies and how they affect adaptation processes and outcomes.

Adaptation needs and activities can be determined by the regulatory and legislative context in which the decision maker (in this case city councils) operate (Palutikof et al., 2019). As such, the role of institutional behaviour in how adaptation options are identified and implemented requires investigation. Rosenzweig (2013) highlights there is a need to deepen understanding on who makes adaptation decisions and how they are made across various institutional, political, legal and cultural contexts. Adaptation decisions are context specific and therefore there is a need to understand who makes adaptation decisions and what information is used. There is therefore a significant knowledge gap surrounding the understanding of practical adaptation decisions occurring in real life settings particularly within the unique context of city level adaptation planning (Arnell, 2010; Capela Lourenço et al., 2015). Patwardhan et al. (2009, p.221), state, “For climate change adaptation it is important to know more how adaptation decision-making might work in practice, as an important part of the knowledge base for adaptation planning and action”.

There is a need for greater research on adaptation in practice. It is argued by multiple authors (Agrawal, 2008; Biesbroek et al., 2009; Fussel, 2007; Klein et al., 2015; Moser & Ekstrom 2010b) that adaptation implementation is restricted by constraints and barriers arising from the social, cultural, economic, institutional and political context in which adaptation is occurring. However, there is limited analysis of how these contextual factors influence and affect decision-making. Janetos (2020, p.176) states, “We [the adaptation community] are often ignorant of most if not all of these critical descriptions of context”. Thus, this thesis is interested in the influences of context on decision-making and decision-support selection.

Lourenço et al., (2014) highlight that practical experience with decision makers to date, has demonstrated that there are a number of challenges in translating theoretical frameworks into practice in real-life adaptation decision-making. Similarly, Patwardhan et al. (2009, p.221) state that “[f]or climate change adaptation it is important to know more how adaptation decision-making might work in practice, as an important part of the knowledge base for adaptation planning and action”. Therefore, there is a need for rigorous and critical assessment of the practicalities of applying different decision-support tools in real world settings. Given that city-level strategies are the locus of action, it is important to understand the process of urban climate adaptation. It is also crucial to understand associated challenges and limitations surrounding decision-making, such as lack of time, resource, experience, support, policy levers and decision support tools, and how this affects adaptation processes and outcomes.

Climate adaptation research must therefore further explore the relationship between theory-based guidance and the complexity of real-life decision-making on the ground. There is limited literature targeting this knowledge gap to date, highlighting that implementation of adaptation decision-making and research alternative decision-support methods for adaptation, is still in its infancy. Further research is therefore required on the knowledge requirements and enabling conditions needed for decision makers to understand risks and uncertainties which affect their decisions (Moss et al., 2012). To aid academic understanding, deeper engagement with and observation of decision-makers is required to explore their knowledge requirements but also their risk perception and decision-making environment and processes (Rosenzweig & Horton, 2013). This knowledge gap has led to the development of Research Objective One (see Section 1.2). As such, this thesis will examine city level adaptation decision-making processes.

Section 3.4 explored how traditional decision-support approaches (such as CBA) used in other fields may not be suitable to the wicked problem of climate change. This is due to the fact that many commonly used decision-supports cannot incorporate and account for the benefits of adaptation, specifically the non-monetary costs, in appropriate ways nor capture uncertainty (Dittrich et al., 2016). For example, this is evidenced by the recent publication of supplementary Green Book Guidance for accounting for the effects of climate change (Defra, 2020). This recent publication recognises that traditional economic evaluation may not be suitable to account for the effects of climate change, nor identify which actions are most resilient to climate change. In addition, it is suggested by Lourenco (2015) that adaptation challenges may require new decision-making approaches as current decision support methods are becoming increasingly unsuitable. This thesis is therefore interested in understanding how alternative decision-support approaches, such as BBNs, can help climate adaptation.

Through a literature review three key knowledge gaps surrounding city-level adaptation decision-making were highlighted: (i) there is limited evidence of how approaches are used in practice and if conceptualisations are reflective of reality; (ii) there is a lack of knowledge or evidence on how exactly adaptation decisions should be made within these frameworks; and (iii) there is a need for further understanding on the influences on decision-making. These knowledge gaps informed the development of the thesis aim and research objectives (detailed in Section 1.2).

## 3.7 Conclusion

Decision-making for climate adaptation, whilst being a relatively new field (as the focus on climate adaptation has only grown significantly in the past decades as described in Section 2.2), is an extremely important one. Adaptation choices will influence the ability of city councils to withstand and respond to climate impacts both now and in the future (IPCC, 2014c). The effectiveness of climate adaptation will be influenced not only by the climate risks, urgency, resources and location of a local authority adapting but also the methods of decision-making employed (Gorddard et al., 2016; Ranger, 2010).

This chapter explored climate adaptation decision-making. Sections 3.1-3.5 introduced the adaptation cycle and the key contextual characteristics that influence the decision-making process. Subsequently it provided a high-level assessment of an array of common decision-making tools used in climate adaptation in terms of their ability to help the decision maker account for the contextual characteristics. Considering this, three key knowledge gaps that require further research were identified. These are: (i) how adaptation decisions are made in practice; (ii) the need to test and assess new decision-making methods; and (iii) the requirement to understand influences on decision-making. The next chapter introduces the research context and methodology used to explore the research objectives.

# Chapter 4: Research Design

> "Action research serves as a bridge for scientists and policymakers to meet each other and to become better informed about what is happening in 'the other world'. This is important, as both hold valuable knowledge and insights. A first function of action research is thus to enhance knowledge dissemination and the valorisation of scientific knowledge. Related to this function, action research contributes to reflection and learning amongst policymakers. It can enhance awareness about climate change and the need for adaptation and can offer insights into alternative strategies and possible instruments."
>
> (van Vliet et al., 2015, p.194)

Chapter 2 established why climate change adaptation in cities is important and the need to explore challenges in practice. Chapter 3 presented the contextual characteristics that influence climate adaptation decision-making and the subsequent need for appropriate decision support methods. Together, Chapters 2 and 3 identified key knowledge gaps that informed the aim and objectives of the thesis. This chapter describes the action research design used in this thesis and introduces the research site of Glasgow City Council (GCC).

This chapter begins by introducing the research design (Section 4.1) and research approach (Section 4.2). The research setting of GCC is then presented (Section 4.3). Finally, a summary is offered (Section 4.4). When appropriate, first-person narrative was adopted to reflect the nature of action research. First person is used to honestly and accurately recount the process and emerging reflections that were experienced throughout the course of this research.

## 4.1 Research Design

This thesis aims to better understand how climate adaptation decisions are made at the city scale through an exploration of Glasgow, UK. In particular, this research develops a contextually rich and reflective understanding of a how a city council interprets and acts upon the concepts of climate adaptation at a strategic and operational level. Exploring and researching urban climate adaptation, necessitates a research approach and methodology which allows one to capture and explore temporal, organisational and political aspects. Action research was thus suitable for such research. This research approach is also supported by the research philosophy of critical realism adopted by the researcher.

#### 4.1.1 What is Action Research?

Kurt Lewin proposed the term ‘action research’ in his 1948 article “Action Research and Minority Problems” (Lewin, 1948) where he described action research as “a comparative research on the conditions and effects of various forms of social action and research leading to social action”. Blum (1955) interpreted action research as “diagnosis of a social problem with a view of helping improve the situation”. More recently, action research has been defined as “a participatory process concerned with developing practical knowing in the pursuit of worthwhile human purposes. It seeks to bring together action and reflection, theory and practice, in participation with others, in the pursuit of practical solutions to issues of pressing concern to people, and more generally the flourishing of individual persons and their communities” (Reason & Bradbury, 2008).

In its simplistic interpretation, action research can be conceptualised as a two-stage process (Blum, 1955). The first is the diagnostic stage analysing the situation and problem context and formulating a hypothesis related to the research domain. The second stage, or therapeutic stage, incorporates experiments to explore their effects in the research setting (Baskerville & Wood-Harper, 1998; Blum, 1955). As such, the hypotheses are tested by a consciously directed change experiment, preferably in a real-life situation.

Reason and Bradbury (2008) identified traits of action research including engaging stakeholders in collaborative relationships, integrating multiple forms of knowledge, being values orientated and motivated to contribute to the ‘flourishing of human persons, their communities and wider ecology’. Action research may alter and develop as the researcher and collaborators deepen their understanding of the research issue and develop competencies as inquirers (Reason et al., 2014).

Therefore, action research is an emergent process that is not possible to be predetermined. As such, a key element of action research across techniques are a cyclical, reflective processes. The cyclical aspect of action and reflection are prominent in definitions of action research including that of Kurt Lewin (1948, p.206) who states that "It proceeds in a spiral of steps, each of which is composed of a circle of planning, action and fact finding about the results of the action'.

The specific aim of action research is to develop 'actionable knowledgeable' which develops knowledge that is relevant and accessible to policy makers, decision-makers and practitioners (Coghlan & Brannick, 2005). Action research intends to address practical concerns in an identified problem context as well as advance the knowledge of science simultaneously; it is about working towards practical outcomes (Buuren & Eshuis, 2014; Reason et al., 2014). It thus has a twinned approach to develop practically appropriate and academically sound knowledge requiring co-learning and collaboration. The orientation of being action driven influences the overall research design, including methods and techniques applied.

Action research encompasses a broad spectrum of research approaches ranging from action inquiry, participatory action research and collaborative action research which are all related in that they aim to develop theories within the research setting itself and do this through intervention experiments (van Vliet et al., 2015). The approaches differ, however, in terms of focusing either on results to solve problems and how much experts are involved or the extent of participation. O'Brien (1998) proposes that accomplishing action research may require the adoption of different roles at various stages of the research process from planner, leader, catalyst, facilitator, designer, listener, observer, synthesizer, and reporter. This research did not intentionally set out to have such diversity of roles but through regular interactions across many years, I undertook all of the above roles. This is illustrated in the Action Research log in Appendix I which shows the different activities undertaken during the research period and what role, I, as the researcher played at each as my relationship with key stakeholders and knowledge of the context evolved and developed.

### 4.1.2 Action Research for Climate Adaptation

Interest in action research is growing from the climate adaptation research community. There is an identified need for more practice-based research on adaptation. Patwardhan et al. (2009, p.224) outline that:

> “Research in adaptation is still emerging as a significant area of scientific inquiry. At the same time, the urgency of action requires significant improvements in understanding, theory and methods and tools pretty quickly. This will not happen unless we are able to achieve the co- evolution of research and practice and create and implement a research agenda that integrates theory and application through active interfaces with adaptation actions and interventions. The core challenge of climate adaptation is in the ever-moving landscape of adaptation as our understanding of future vulnerability unfolds”.

There are a range of ways action research may be undertaken. Buuren and Eshuis (2014) provide an assessment of how the varying methods and processes of action research relate to the field of climate adaptation. They highlight that action research approaches may differ in their approaches but also the levels of intensity. The intensity is influenced by the level of interaction between researchers and practitioners as well as the width and depth of these interactions according to Buuren and Eshuis (2014) and Edelenbos & Klijn (2006). Interaction width relates to with whom the researcher interacts, in other words is it a narrow or wide selection of actor types. Fung (2006) examines levels of action research interaction and intensity and proposes that interaction may be with selected professional of all types, elected representatives, selected stakeholders, or self-selected stakeholders open to all. Interaction depth relates to the instances of meaningful participation, or the extent to which participants shape processes and outcomes (Edelenbos & Klijn, 2006).

## 4.2 Research Approach

The motivation to explore adaptation in practice and address real-world challenges lent itself to an action research approach being used for this research. Within this thesis, action is interpreted as activities which contribute new thinking and/or activities. Action also refers to having stakeholders try out new decision-making methods and processes and subsequently helping them to reflect on different concepts through interviews. For instance, the co-creation of Bayesian Belief Networks (BBNs) and Qualitative Probabilistic Networks (QPNs) to support decision-making (as described in Chapters 8 and 9). The benefits and limitations of action research generally will now be presented.

### 4.2.1 Benefits of action research

Action research offers several benefits over other research approaches when studying a real-world phenomenon. Firstly, it enables a richness of information to be gathered as its purpose is not centred solely about data collection but also about understanding the context of research and building collaborative understanding with stakeholders (Edelenbos & Klijn, 2006). As such, action research is one way to gain valuable tacit knowledge of the decision-making process and factors that influence the process (such as relationships and organisational culture). The depth of knowledge and understanding can extend beyond what is possible through secondary data or even semi-structured interviews.

Secondly, action research is one approach which enables the identification of a range of barriers as well as providing the opportunity to propose and test out interventions (Reason et al., 2015). Research Objective 2 was to assess the value of Bayesian Belief Networks (BBNs) and adjusted Qualitative Probabilistic Networks (QPNs) as decision-making methods to support climate adaptation decision-making within a city council and address challenges identified via Objective 1. As such action research offered the opportunity to test these approaches in real-life settings.

Action supported via action research, can help build understanding of stakeholders involved, leading to enhanced organisational capabilities and adoption of new practices, given the goal of action research is to improve situations (Reason et al., 2015). In the SAGE Handbook of Action Research (Reason et al., 2015) Marja Liisa Swantz notes “I do not separate my scientific inquiry from my life”. This is particularly pertinent for this PhD project as I became a practitioner whilst completing this research and therefore was driven by both a personal and professional commitment to deepen my understanding of climate adaptation decision-making in a real-world setting. In 2017, I began working on the Adaptation Scotland programme, a Scottish government funded initiative which supports organisations, businesses and communities to adapt to climate change. As such, this research was carried out part-time alongside my practitioner role, which gave me a longer time to build relationships and conduct action research.

This thesis was also motivated to use action research because climate adaptation decision-making is a relatively recent research topic (particularly for those tasked with performing it) (Power et al., 2018). Due to climate adaptation decision-making's relative immaturity (in comparison to more established fields of decision science), there are limited longitudinal studies available. Contributions are typically high-level case studies which draw on interviews, which preclude the researcher from being embedded, or observing the heart of the problems associated with the process. As such this research wanted to focus on 'real' decision makers within a relevant context.

#### 4.2.2 Limitations of Action Research and Mitigants within this research

There are several criticisms of action research. The first criticism suggests action research is synonymous with researchers becoming academic consultants focusing on practical action rather than rigorous academic research (Davison & Martinsons, 2007). A second criticism is that since it is undertaken in one organisation, it is not generalisable, a positivist criticism focusing on developing theories. The third being that the informal nature of action research means that not all steps are always recorded, opening it up to criticism on lack of rigour (Davison & Martinsons, 2007; Wedekind, 1990).

To begin to address these critiques, knowledge development should be captured rigorously and explicitly. Contributions that have sought to differentiate action research from consultants (Baskerville & Wood-Harper, 1998; Davison & Martinsons, 2007) highlight that whilst consultants solely work for a client, action researchers are bound to share their results with academic or research community. This means that action researchers must "serve and satisfy two demanding masters" (Davison & Martinsons, 2007, p.389). I addressed these criticisms of action research by clearly communicating that I was a PhD researcher and not a consultant, regularly updating stakeholders on the progress of my research and having self-awareness and flexibility to alter research direction as and when appropriate. In addition, I interviewed adaptation practitioners in Northern Ireland and the Netherlands following data collection. Their responses supported my findings from Glasgow (as described in Section 6.4.5 and Section 10.6).

Action research by its nature is flexible and conscious of context and therefore must be applied sensitively and designed to address the organisation problem context (Davison & Martinsons, 2007). This was central to my research as I was conscious of the process ongoing in Glasgow and indeed had to alter my research to align with ongoing activities. I recorded all notes openly and honestly and used multiple methods (including participant observation and semi-structured interviews) within the action research design to reduce subjectivity and enable deeper analysis.

As established in Chapters 2 and 3, climate adaptation decision-making is a relatively new concept for local authorities, but an area of incredible importance and consequence. City councils must now learn to interpret and operationalise adaptation guidance and select a decision-making method most suitable for their adaptation needs.  Chapter 3 highlighted the key knowledge gap in the literature with regards to understanding and evaluating the usefulness of frameworks and decision support methods when used in practice (Capela Lourenço et al., 2014; Stults et al., 2015).

To address this knowledge gap, it was necessary to develop a tacit and deep understanding of the real-world challenges associated with city level climate adaptation decision-making within GCC. To do this, an action research approach was adopted to gain empirical learnings and support experimentation to advance conceptual understand of practice-based processes within the research location of GCC. This thesis followed the development and decision-making processes of the Glasgow Resilience Strategy and the Glasgow Adaptation Strategy and Action Plan during 2015 to 2020. The next section introduces the research setting of Glasgow City Council.

## 4.3 Research Setting: Glasgow

In order to achieve Objectives 1 & 2, this thesis undertook a detailed longitudinal case study of the development of the Glasgow Resilience Strategy and Glasgow Climate Adaptation Strategy and Action Plan during 2015 to 2020 (GCC, 2016a). The study evaluated the decision-making challenges GCC faced when developing and operationalising such a strategy and action plan. This section (4.3) therefore provides the context, background and rationale for selecting GCC as the object of study. It is divided into three sections. The first section (4.3.1) provides the wider context of climate adaptation in Glasgow and Scotland. The second (4.3.2) provides a brief history of the city.

### 4.3.1 Climate Change Adaptation in Scotland

This thesis posed the research question: What challenges influence climate adaptation decision-making currently and what is the value of using alternative decision support methods? Research was underpinned by two research objectives (described in Section 1.2). Given that research was interested in city-level climate adaptation decision-making in practice and wanted to utilise action research, research was undertaken within a city council. Glasgow, Scotland was selected as the geographic region for this study. Scotland has been widely promoted as a leader in tackling the climate emergency (Scottish Government, 2020b). The legislative framework for climate adaptation in Scotland is introduced here.

Action on climate change in Scotland is guided by both UK and a Scotland specific legislation. There are two key pieces of legislation: the UK Climate Change Act 2008 and the Climate Change (Scotland) Act 2009. The UK Climate Change Act requires a Climate Change Risk Assessment (CCRA) to be produced every five years, led by the Committee on Climate Change (CCC). It is the basis for adaptation policy in both Scotland and the UK. The Scottish Climate Change Adaptation Programme (SCCAP) addresses the impacts identified for Scotland in the UK Climate Change Risk Assessment (CCRA) and sets out the Scottish Government's objectives in relation to adaptation to climate change (Scottish Government, 2019b).

The Climate Change (Scotland) Act 2009 places a duty on public bodies to act "in the way best calculated to help deliver" the SCCAP. Public Sector Climate Change Reporting Duties set out in the Climate Change (Scotland) Act 2009 requires relevant public bodies to prepare reports on compliance with their climate change duties. Mandatory reporting on compliance with the Public Bodies Duties was introduced in 2015 and is required to be completed annually. Information provided through this reporting process is used to inform Scottish Ministers' annual progress report and the biennial independent assessment report. Reporting must cover climate change progress including adaptation and is required from all public bodies, including city councils.

### 4.3.2 Introducing GCC

This research explores the decision-making processes lead by GCC between 2015-2020. As such, a brief introduction to the governance and operational structure of the council is offered here. In terms of governance, GCC is headed by the ceremonial position of the Lord Provost of Glasgow who is a general civil leader (GCC, 2020). GCC has an executive council headed by the Leader of GCC. At the time of writing, GCC was governed by a minority from the Scottish National Party (SNP). In terms of structure and operations, GCC has a number of Arms' Length External Organisations (ALEOS) which provide services to and on behalf of GCC, including City Building Glasgow, City Parking, City Property, Glasgow Life and the Integration Joint Board. GCC is one of Scotland's largest employers with over 20,000 staff (GCC, 2019). GCC work towards a Strategic Plan (2017-2022), a publicly available strategy which outlines the priority themes and commitments to be delivered by GCC as well as its services and arm's length organisations (GCC, 2017).

In relation to climate change adaptation, the Sustainable Glasgow initiative was established by GCC. Formed in 2010 and led by GCC it was the first group created to support Glasgow's aspirations to be one of the greenest cities in Europe by 2020 (Bellingham, 2010). The Sustainable Glasgow initiative is a partnership that brings together stakeholders from housing, communities, business, universities, enterprise and education. The partnership aimed for Glasgow "to become one of Europe's most sustainable cities by 2020 – with a focus on improving quality of life in the city, protecting the environment and developing a green economy with sustainability top of the agenda," (Glasgow Convention Bureau, 2019, p.1). The initiative focused on climate change policy, low carbon activities and district heating. A Sustainable Glasgow team existed within GCC to support the partnership, with staff numbers fluctuating between two to five team members during the time of this research.

In 2010, GCC also published its Climate Change Strategy & Action Plan (GCC, 2010). Priorities for action set out in the document relate to sustainable consumption and production, green energy production, reduction of greenhouse gases, natural resource protection and sustainable communities, with minimal acknowledgement of climate adaptation. In 2015, Glasgow was selected as part of the Rockefeller 100 Resilient Cities project and subsequently produced the Glasgow Resilience Strategy in 2016, which only minorly addressed issues of climate adaptation (GCC, 2016a). In recognition of this oversight, in 2017, GCC began creating a city-wide Climate Resilient Glasgow Adaptation Strategy and Action Plan. GCC set up a task group to drive forward strategic adaptation work within the city to be aligned with the resilience strategy's actions and recommendations. There was also a commitment to ensure alignment with regional aims including the work of the Climate Ready Clyde Partnership, a regional climate adaptation partnership that GCC was a paying member of and active contributor to (Climate Ready Clyde, 2020).

GCC was thus selected for the site of action research for the following reasons:

i. As a result of the adaptation activities undertaken in Glasgow (outlined above), Glasgow was identified as an interesting research area to address the two objectives of this thesis. Glasgow is or has also been part of a range of international programmes and partnerships on the topic of climate adaptation and resilience such as the Rockefeller 100 Resilient Cities (Rockefeller Foundation, 2017), URBACT Urban Resilience Programme (ERDF, 2021) and the Smart Mature Resilience research project (SMR, 2018). In addition, GCC was an active member of Climate Ready Clyde, a regional adaptation partnership working together to develop a climate adaptation strategy for the city region (Climate Ready Clyde, 2020).

ii. The timing of my research coincided with key strategy and action plan development processes, allowing me to follow the entire decision-making process. Working as a climate adaptation practitioner on a Scottish Government funded advisory service, I was also able to draw on my experience of adaptation activities in other public bodies in Scotland and the wider contextual setting with which the study is embedded. It also provided GCC with the confidence to allow me to be involved in activities relating to the formation of the strategy and decision-making thereby allowing me to undertake action research.

iii. GCC allowed me access to their internal processes, including to observe relevant meetings (such as steering and working group meetings), introduced me to key contacts and supported in arranging interviews. Such generous access is rare to get, yet critical to allow the researcher to gain a full understanding of the context surrounding the decision-making process. Limited access to closed door conversations is likely the reason why city level adaptation case studies in the literature to date have remained relatively high level in their depth of analysis and speculative.

As such, Glasgow City Council was selected as the location of this research. It will be referred to as GCC throughout the remainder of the thesis. To provide historical context for the city, a brief history of Glasgow is provided in the following section (Section 4.3.3). The city's history is further referenced in Chapter 8 when exploring determinants for resilience.

#### 4.3.3 A brief history of Glasgow as it relates to climate adaptation

From the 18th century onwards, Glasgow was one of the main industrial cities in the United Kingdom. Glasgow was an industrial and commercial centre, often known as "the second City of the Empire" (Tretter, 2009). Ship-building and engineering made up of the majority of industry (Montanari, 1989). This changed in the mid-20th century. An international economic crisis and lack of development of new industry combined to create an industrial desert in the city and rising unemployment in the 1970s (Montanari, 1989).

Following the Second World War, the British Government aimed to achieve industrial diversification and decentralisation of industrial and residential centres. This led to the creation of 'New Towns' immediately surrounding Glasgow including Cumbernauld, East Kilbride and Irvine. These 'new towns' relocated people and industries from the city centre to the wider region. Glasgow's redevelopment did not focus on the economic, housing or health needs of the city but instead looked to economic modernisation to achieve growth, and thus attention was focused on development of newer industries primarily located outside of Glasgow thereby leading to the creation of these distant New Towns. The creation of the New Towns caused selective removal of specific subsets of the population who were typically higher skilled workers (Pacione, 1979; Urban, 2018).

Glasgow, however, later reinvented itself through transitioning from an industrial to service-based economy and through capitalising on its cultural resources, for example through hosting the European City of Culture festival and Garden Festival in 1990. The period since the Garden Festival, has seen Glasgow excel as a destination for major conferences and sporting events, even the European Climate Change Adaptation (ECCA) conference was held in the city in 2017. As Fry (2017, p.319) states about Glasgow, “It could well be argued that modernism has helped to liberate the city from its inferiority complexes. The city has less confidence about architecture, but its urban history and its openness to international contacts create future scope for renewal of the typical Glaswegian combination of swagger and style.” From the beginning of the 21st century, as Glasgow’s service and cultural economy began to boom, its population increased and Glasgow is now the largest city in Scotland, and the third largest in the United Kingdom, with a population of 635,640 (National Records of Scotland, 2021).

Glasgow, as a result of the rapid growth and subsequent decline of its industrial economy, can be considered a post-industrial city. Although the economic outlook of the city has been steadily improving in the past decades, aspects of the city's landscape and cultural processes still exhibit the residual effects of de-industrialisation. Extensive and prolonged industrialisation took a heavy toll on the natural environment. Social impacts compound these effects where, for example, population resettlements (Meighan, 2013) created excesses of chronically vacant and derelict land and fractured or empty neighbourhoods. The legacy of these past environmental impacts can be seen today in some areas of Glasgow where average measures of health, wellbeing and life expectancy are low compared to neighbouring areas and other post-industrial UK cities of similar size and demographics (Walsh et. al, 2016). Although not ubiquitous, some areas are consistently placed within the poorest 5% of areas in the Scottish Index of Multiple Deprivation (SIMD) (Scottish Government, 2020c).

Glasgow may thus be considered as a dichotomous city. It has a legacy of innovation, wealth and opportunity whilst at the same time has historically been home to some of the world's lowest life expectancies, poorest health outcomes and grave deprivation (Hanlon et al., 2006; Walsh et al., 2016). It was these parallel worlds which have both stimulated and enabled the city to take action on resilience (broadly in the holistic sense of the word) and in relation to climate adaptation (Naylor et al., 2019). These historic and current pressures and impacts on Glasgow's landscape create the context within which climate resilience in Glasgow takes place. This tight coupling between social and ecological history, and the future environmental risks the city is facing, mean that a holistic approach that addresses the social, ecological and economic activities of the city, are likely to prove most fruitful (Tompkins & Adger, 2004).

Despite the challenges faced by post-industrial cities such as Glasgow, there are significant opportunities for climate adaptation and resilience. An example being the innovative use of excess vacant land to manage extreme heat or precipitation events (Newman et al., 2019). Donald Carter, director of the Remaking Cities Institute at Carnegie Mellon University, suggests that post-industrial cities can play a role in the twenty-first century that parallels the role they played under very different circumstance in the nineteenth and early twentieth centuries (Carter, 2016, p.103). It is perhaps fitting that cities which were the birthplaces of the Industrial Revolution are now becoming (either through choice or necessity) the first at tackling the impacts of climate change. It is for these reasons that this thesis focuses on climate adaptation activities in Glasgow from 2015-2020.

This section has provided a brief introduction to the history of Glasgow and the institution of GCC. I explored this topic further in a book chapter I co-authored entitled, "Our 'Dear Green Place': Glasgow's transformation from industrial powerhouse to sustainable city" (Naylor et al., 2019) within the book Transforming Glasgow: Beyond the Post-Industrial City (Kintrea & Madgin, 2019).

### 4.3.4 Action research in Glasgow City Council

This thesis explores the theoretical foundations of decision-making as well as understanding the practical aspects, challenges, and methods of decision-making for climate adaptation in practice. As stated previously, within this thesis, action is referred to as having stakeholders try out new decision-making methods and processes and subsequently helping them to reflect on different concepts through interviews. Contribution, or the 'action' part of action research, consisted of proposing, testing, and reflecting on the use of BBNs and QPNs to aid GCC's decision-making (as described in Chapter 7).

Building relationships and rapport with research partners was commenced at the earliest possible opportunity. This research heeded the advice of Lonsdale and Goldthorpe (2012) for recommendations for researchers to begin open discussions with stakeholders[17] as early as possible. For instance, I began observing GCC meetings in the first month of my PhD in October 2015. Through these preliminary conversations, I was able to speak with the problem owners in GCC to understand their context and begin to devise a methodology to address their identified challenges as well as aiming to contribute to outstanding academic research gaps.

To achieve this, I (as the action researcher) became embedded within the decision-making process of GCC through building strong trust-based relationships with the individuals within GCC responsible for managing the decision-making process for climate resilience. In doing this, I was given unique access to observe and contribute to internal discussions and meetings. I also supported and facilitated meetings, events, and workshops. Becoming involved within the decision process (i.e., attending meetings but also being actively involved as facilitator and host of some meetings) from the outset of my research allowed me to develop a contextually rich understanding of how one local authority implements climate adaptation guidance and makes related decisions, as well as design a sensible and effective research approach from the start of the research. Discussion and reflection on the research

[17] The term stakeholder within this thesis refers to individuals who were involved in GCC's adaptation work, this included internal GCC council staff as well as external organisations who supported adaptation action planning and implementation.

findings (Chapter 10) explores the transferability of this research process and findings.

Through action research, I was able to develop a granular understanding of GCC's experience of managing the process of adaptation decision-making which allowed me to identify challenges (to address Objective 1) that may not have been visible through a more standardised case study approach, such as solely relying on interviews or questionnaires. Adopting an action research approach also allowed me to develop and test a decision support method that were pertinent to the research setting thereby addressing Objective 2. Whilst this action research sought to engage many stakeholders in the research process, given the role of the adaptation lead in the council as the focal point of adaptation in the organisation and decision-maker for the strategy and action plan, a large proportion of time was spent with her (from conversational interviews to participant observation).

To highlight again that I became an adaptation practitioner during my PhD journey. This presented a need to differentiate my roles as a PhD student and Adaptation Scotland staff with GCC. My data collection with GCC formally ended in February 2020 and since that time I have supported them in a professional capacity, from supporting the council with benchmarking their adaptation progress to commenting on drafts of the developed adaptation plan. My PhD experience enabled and encouraged me to become a more reflective practitioner in my professional role. This supported me to identify and recognise many of the challenges to adaptation decision-making in GCC (explored in Chapter 6) in other local authorities and public bodies in Scotland.

## 4.4 Conclusion

The rationale behind this research design was derived from the need for practice based empirical research on an emergent and pressing issue. The previous chapters have highlighted the important role and responsibilities cities and local authorities face in relation to climate adaptation as well as the challenges in lack of international and national legislation, directives, resourcing, or funding. An introduction to Glasgow and GCC was offered in this chapter as contextual basis to aid understanding of the discussion in the findings chapters 6, 8, 9 and 10 which present research undertaken within GCC. The following chapter, 5, details the methodology used to address research Objective 1.

# Chapter 5: Methodology for Research Objective One

This chapter details the research methods that were used to conduct action research to address Research Objective One. By conducting an in-depth longitudinal action research study of city level adaptation decision-making in Glasgow (Scotland) from 2015-2020, this thesis presents unique findings on the process used for decision-making as well as learning on the broader context in which decision-making occurs and the data and information used. The overall aim of the action research in relation to Objective One was to collate and analyse empirical information on current decision-making processes and influences on decision-making.

The methodology presented within the remainder of this chapter outlines the approach taken and methods used. The methodology was developed iteratively with research methods and questions being refined and altered over time which is common for an action research approach (Agee, 2009; Kock, 2003). Due to the nature of action research and the role the researcher played in the problem context, it was decided to write this thesis in first person, where appropriate, to clearly articulate what was the opinion and reflection of the researcher. As such, when the opinion of the researcher is being presented or an argument is being made based on researcher's view and understanding, "I" will be used.

The chapter is structured as follows. Firstly, the research methods for Objective One are summarised in Section 5.1. Then each research method is introduced individually which includes participant observation (Section 5.1.1), Local Climate Impacts Profile

(Section 5.1.2), semi-structured interviews (Section 5.1.3), questionnaire (Section 5.1.4). Section 5.2 then presents the method of data analysis for Objective One and then Section 5.3 concludes the chapter.

## 5.1 Research methods for Objective 1

Objective 1 was to identify the challenges influencing current city-level adaptation decision-making within the real-world context of a city council developing an adaptation strategy and action plan. Data collection to achieve Objective One consisted of research on the following:

**Glasgow Resilience Strategy -** Research on the Glasgow Resilience Strategy (GRS) which included: (i) 75 hours of observations between September 2015 and September 2016 on the various resilience strategy development meetings; (ii) attending 5 steering group meetings, 6 working group meetings and 12 workshops and (iii) 7 semi-structured interviews (Appendix II presents the interview questions).

**Climate Adaptation Strategy -** Research to study the development of the climate adaptation strategy and action plan, a total of an additional 125 hours of action research was undertaken between September 2016 and February 2020 on the various climate adaptation strategy and action plan development processes. This involved (i) attending 8 task group meetings and 12 events and workshops and (ii) conducting 18 semi-structured interviews (Appendix III presents the interview questions) and unstructured interviews with the Adaptation Lead during 2016-2020. In addition, two questionnaires were used to collect data. One questionnaire was distributed at an internal GCC adaptation workshop in May 2017, referred to as questionnaire #1 (Appendix IV), and the second at three Climate Resilient Glasgow workshops in August 2017, referred to as questionnaire #2 (Appendix V).

This section details the methods used to obtain research Objective One. As this thesis was interested in understanding challenges to adaptation in practice, a mixed methods approach involving data collection via (i) participant observation; (ii) media analysis; (iii) a questionnaire; (iv) semi-structured interviews; and (v) conversational interviews, was applied. These methods were chosen because each provides a different perspective, which collectively enables a holistic understanding of the research setting. Some activities were undertaken in tandem (i.e., participant observation ran throughout the period of study for research Objective 1), whereas other research activities followed on and were informed by previous actions (for instance the media analysis identified climate events which were further discussed in the semi-structured interviews). Findings from each method of data collection were triangulated where appropriate. Each of these methods are presented here.

#### 5.1.1 Participant observation

Participant observation is a research method relating to observing and in some instances interacting with a specific group (Herbert, 2000). Baskerville & Wood-Harper (1998, p.101) state that the method of participant observation is "fluid in structure, chiefly because it is difficult to control human interaction in social settings". This research responded to this fluidity by being responsive and agile to the changing research context (for instance, the approach to address research Objective Two utilised learning garnered via action research addressing Objective One).

Participant observation is often used in ethnography, where a researcher spends substantial time observing and interacting with a specific group of people, which allows them to understand the group's view and relations (Herbert, 2000). Participant observation thus relates to the researcher becoming directly involved as a participant within the research context (Baskerville & Wood-Harper, 1998). It is also underpinned by a reflective process. For instance, research diaries were kept throughout the research journey. Such immersion can offer a rich picture that enables researchers to identify and understand underlying processes which would not have been observed through other methods.

In this research, I undertook observations within different settings where climate adaptation and resilience where being discussed, namely meetings, workshops, and events. From 2015-2016, I attended meetings and workshops to develop Glasgow's Resilience Strategy (GRS). This ranged from attending project meetings at GCC, and external workshops, events, and conferences. Following the release of the GRS in September 2016, GCC decided to create a climate adaptation strategy and action plan. From 2016-2018, I observed and participated in the Climate Resilient Glasgow

taskforce. I was able to observe relevant meetings of the GCC Climate Adaptation Taskforce[18], including attending seven meetings and five all day workshops of the taskforce. From 2018-2020, I had regular interviews with the adaptation lead to understand the process.
A total of 200 hours were spent following these two strategies (the Glasgow Resilience Strategy and the GCC Climate Adaptation Strategy and Action Plan) being developed. Through undertaking action research, I was able to observe and participate in both public and closed-door meetings which allowed me to track the development of the strategies over time. In addition, I was able to witness behaviour of and between stakeholders first-hand. In relation to the development of the GCC Climate Adaptation Strategy, I was able hear the reflections, perceptions, and feelings of the main decision maker, who was the adaptation lead within the council. She was responsible for developing the adaptation strategy and action plan. This individual is typically referred to as the decision-maker throughout this thesis.

At the meetings, workshops, and events I attended and observed, I recorded meeting minutes, notes, and reflections in field notebooks. At these meetings and events, I acted as a 'participant-observer'. My level of participation differed during meetings, but I would often take a backseat observation role unless asked for input. Whereas in workshops I played a much more active role, in many instances co-designing workshops, planning of the event and acting as a facilitator on the day. During participant observation, I gathered minutes or other documents produced or prepared for the meetings. I also captured research impressions in seventeen field notebooks worth of notes during the research period.  Finally, these notes along with project documents and learnings from informal off-the-record discussions and conversational interviews allowed me to reflect on what I had learned about the context and process to begin to identify emergent themes and what to pay attention to at further meetings or areas of interest to follow up further.

[18] The Glasgow Adaptation Taskforce was a working group set up to support the development of the city's climate adaptation strategy. It was organised by GCC with involvement of partner organisations such as University of Glasgow, Glasgow Caledonian University, and other public bodies who fed into the adaptation strategy development process.

In relation to how participant observer data was recorded, I found no alteration of behaviour when taking handwritten notes at meetings, as many other attendees also recorded notes. I found a noticeable difference, however, in responsiveness and openness during discussions and interviews when I requested if I could audio record. As such, I captured responses through written shorthand rather than audio recordings to allow free and honest conversations. My notetaking involved the following activities: (i) noting events and decisions occurring within the meeting; (ii) recording verbatim quotes where possible; (iii) short notes to myself about key tensions, disputes, or disagreements in relation to decisions; or (iv.) flagging key personnel or policies to research further. This resulted in staff having frank and open conversations with me about the trials and tribulations faced during the decision-making process. Undertaking action research and collecting data through participant observation was an iterative and often opportunistic process. Being reactive and open is a key tenet of action research and reflects on my ability to build rapport and be accepted as a valued contributor to discussions to be invited to further events.

### 5.1.2 Media Analysis for a Local Climate Impacts Profile (LCLIP)

As part of my participant observation role, I sought to understand the work of the Climate Resilient Glasgow taskforce including their activities and processes. It was also necessary, in terms of Objective 1, to learn about the tools and guidance they currently used to support climate adaptation decision-making. One way in which I did this was to contribute directly to their work, through undertaking a Local Climate Impacts Profile (LCLIP). The LCLIP is a common tool used within the Adaptation Wizard to collect data of experienced climate impacts and adaptation responses, via media analysis and interviews (as described in Chapter 3).

To undertake the LCLIP and identify local climate impacts reported in the news, I conducted a media trawl for the period 2007-2017 to identify articles referencing weather events and related impacts in Glasgow. The Nexis UK database was used, which has articles and newspapers at various geographies, which can be searched using different terms (Lexis Nexis, 2021). A systematic study was completed using search functions for key terms following the guidance outlined by the former UK Climate Impacts Programme (UKCIP, 2018). Key words searched for included

Glasgow as the location and then thirteen weather-related terms including “rain”, “drought”, “ice”, “snow”, “heatwave”, “high temperatures”, “wind”, “gales”, “flooding”, “tidal surge”, “fog”, “lightning” and “storms”. A total of 163 articles were identified containing key climate words in relation to Glasgow City during the study period. These articles were analysed by searching for the weather type, impact and consequence and recording these in an Excel spreadsheet (example in Figure 5.1). This enabled quantitative analysis of the frequency of weather types and climate impacts being reported for Glasgow. This highlighted key trends and identified case study events, which were referred to within the semi-structured interviews.

| Source | Headline | Date of the story | Summary of news story | Impacts |
|---|---|---|---|---|
| The Herald | Severe weather warning is issued as gale-force winds up to 90mph lash Scotland | 09 January 2008 | Strathclyde Fire and Rescue Service said it attended about 70 weather-related incidents between midnight and 2am.A spokeswoman said reports of dangerous structures and fallen trees, accounted for many of the calls. Firefighters attended a report of a partial collapse of the gable end of the historic Hutchesons' Hall in Ingram Street, Glasgow. | Damage to buildings |
| The Sun | A&Es swamped by winter fallers | 04 December 2008 | People suffering breaks and sprains by slipping on ice, road accidents. NHS Greater Glasgow and Clyde recorded their busiest ever day on Tuesday - with 2,000 people needing emergency treatment. Two patients are in intensive therapy units with serious head injuries after slipping on ice. Numbers attending the five A& E departments were 20 per cent above the previous one-day record. Glasgow's Victoria Infirmary recorded a 40 per cent rise. | Injury |
| Evening Times (Glasgow) | Flash Floods Cause Chaos | 23/09/10 | Flooding also hit train services in Glasgow between Dalmuir and Garscadden. Trains from Motherwell to Dalmuir stopped at Garscadden, where alternative transport was provided. Dalmuir/Springburn trains were withdrawn, but Milngavie/High Street services were extended to Springburn. Helensburgh services were being diverted via Singer. The A813 Stirling Road in Alexandria, Dunbartonshire, was also closedby flooding. Strathclyde Fire and Rescue said it had received 117 calls in just six hours throughout the region after a night of torrential rain affected roads and rail routes. | Travel Disruption / Delays |
| Evening Times (Glasgow) | Dig out the oilskins ... it's gonna get wet, wet, wet! | 05/12/15 | Amber alert for heavy rain across Glasgow as Storm Desmond strikes UK. The organisers of Glasgow Loves Christmas were forced to close the George Square attraction yesterday due to high winds | Changes to leisure activities |

*Figure 5.1: Excerpt from LCLIP illustrating different categories of climate impact information recorded*

News reports draw attention to some stories whilst obscuring others (Hodgetts & Chamberlain, 2013). Therefore, studying media reporting of climate impacts can reveal quantitative information on rate of reporting on the topic but also about how stories are framed. Content analysis can be used to study news by taking samples over a period of time. Quantitative content analyses of news texts have limitations in that it does not explore how the news was communicated, received, or interpreted by viewers. It allows the documentation of trends in news representation but not the wider issues of construction and interpretation (Hodgetts & Chamberlain, 2013). This limitation is acknowledged but was not much of an issue as I was concerned with climate impact mentions in terms of frequency of reporting rather than the composition of articles or how they were interpreted by readers.

I undertook the LCLIP myself not only to contribute to research Objective 1 (which it did), but also as a way to gain additional trust and access to GCC. My role leading the

LCLIP enabled the decision-maker to invite me to additional meetings. This work was not performed as consultancy, but instead was a research-based practical activity which supported the reciprocation of contributions of time from GCC staff members.

#### 5.1.3 Semi-structured Interviews

Semi-structured interviews are a qualitative method for data collection where a researcher asks participants predetermined open-ended questions (Given, 2012). As they are open-ended questions, there are no fixed responses and interviews can be adapted within the interview session, for example by selecting appropriate questions in response to what has been stated. The process of semi-structured interviews involves creating interview questions, drafting an interview protocol, identifying informants, conducting and recording the interview and analysing and reporting the findings (Rabionet, 2011). Semi-structured interviews are advantageous in that they have the potential to uncover previously unknown issues (as opposed to a structured interview), provide flexibility with some broad comparisons across interviews and can provide clarity to complex subjects through clarifying follow-up questions (Wilson, 2014). However, weaknesses of semi-structured interviews include the ‘interviewer effect’ influencing what participants are willing to share, bias or cues influencing interviewee’s answers and too much flexibility amongst interviews may make comparisons difficult (Wilson, 2014).

Semi-structured interviews were completed with relevant stakeholders, individuals involved with or contributing to the strategies being studied (GRS and GCC Climate Adaptation Strategy and Action Plan). The findings from the interviews contributed to research Objective One in that they aimed to understand what data, tools, methods, and processes wider stakeholders were using to make climate adaptation decisions. Interviewees were identified through their participation in GCC’s climate work either previously or currently and their contact details provided by the sustainability officer at GCC. The interviews were semi-structured to allow for flexible conversation. The broad themes covered in the interview protocol included (i) previous experiences of severe weather; (ii) how the service, department or organisation was affected; (iii) data and evidence availability and needs; and (iv) identifying if and how climate adaptation decisions were being made currently (see Appendix III interview questions). As is the case with semi-structured interviews, there was flexibility in the approach and questions were selected based on interviewee's contributions (as such not all questions were addressed in every interview).

In addition, regular interviews (at least once a quarter throughout 2017-2019) with the GCC adaptation lead were undertaken. These were less structured, more informal conversations aimed at gaining updates on progress, exploring barriers and enablers to adaptation decision-making and policy development. The interviews with the adaptation lead (the decision-maker) were recorded via handwritten notes. Information from interviews was used to correlate media reports, search for media coverage and compile narrative around certain weather events as case studies.

#### 5.1.4 Stakeholder Questionnaire

Questionnaires consisting of a set of standardised questions in a fixed order, used for data collection on a certain topic (Trobia, 2011). Questions may be open-ended where respondents reply in their own words or close-ended which have set response options and can be statistically analysed (Trobia, 2011). Lietz (2010) suggests using general terms to reduce cognitive load for questionnaire respondents, break complex questions into shorter simpler ones, give examples where appropriate and use specific rather than vague terms such as probably or perhaps. The questionnaire asked simple questions, as much as possible.

Once analysis of the media reports and semi-structured interviews had been completed, a subsequent workshop was then held at GCC in May 2017 to present and discuss preliminary findings from the LCLIP.  At this meeting a questionnaire was distributed amongst the participants (n= 12) to gather insight on the type and format of data that was useful for adaptation strategy development and decision-making. It was comprised of closed and open-ended questions concerning the state of adaptation and preparation in the municipality and the perceived barriers to climate adaptation (See Appendix IV for questionnaire).

### 5.2 Objective 1 Data Analysis

Thematic analysis was used to analyse the data collected through participant observation, questionnaires, and semi-structured interviews during this study. Thematic analysis is a form of data analysis including identifying, organising and interpreting themes in textual data (King & Brooks, 2019). Thematic analysis offers a way to make sense of rich qualitative data sets. Through identifying themes and condensing findings one can communicate important elements to an audience.  Two key stages of thematic analysis include (i) defining themes and (ii) organising themes into a structure. A proposed structure should illustrate and help understand conceptual relationships between emerging themes. Braun & Clarke (2006) in their seminal paper present a form of thematic analysis that is a six-step procedure that advocates for a recursive as opposed to linear process.

Due to the non-linear nature of the action research approach and relationships built during this research, I focused less on proceduralism, examining meticulously how to follow set procedures, and instead considered how to respond imaginatively and appropriately to the data. Preliminary coding was used by reading data, interview transcripts and set of field notes, whereby sections of text that related to the research question were highlighted and summarised. Then clustering was undertaken by grouping emerging themes into clusters, with repetitions between them removed and some hierarchical relationships identified (King & Brooks, 2019). The Pettigrew (1990) Context, Content, Process (CCP) framework was used to analyse and present the findings (described in Section 6.3).

Data from meetings and workshops were captured in a number of field-notes, these reflections and recordings were made in real-time and then later transferred into digital format. I transcribed these field notes when certain phases of strategy development ended offering the opportunity to reflect on project phases as a whole and work collectively but whilst still fresh in one’s memory. This processing of data during the research project allowed me to develop clarity, identify any gaps in my understanding or knowledge which I could address in further interviews or query during informal discussions and start to make sense of the process and how it related to academic literature that I was reviewing at that time.

As a result, the analysis presented is inductive in nature whereby different forms of evidence were collated and triangulated to explore how urban climate resilience occurs and why it does in such a way. This analysis necessitated a temporal and chronological reflection that was complemented by procedural analysis. Adaptation in practice can be a stop-start process, as was the case in this study. It was therefore important to reflect on the evolution of decision-making and how this changed over time during my research.

## 5.3 Conclusion

This chapter detailed the research methods used in this thesis. To achieve research Objective One, mixed methods including participant observation, media analysis, interviews and questionnaires were used and were detailed in Section 5.1. The following chapter presents the first findings in relation to Objective 1 in Chapter 6. The methodology used to achieve Objective 2 is presented in Chapter 7 and the resulting research findings in Chapters 8 and 9.

# Chapter 6: Influences on city-level decision-making within the Glasgow Resilience Strategy and Climate Adaptation Plan

> "Despite the broad consensus and very high confidence in the literature that institutions matter for climate adaptation, there is very little confidence and agreement about two critical questions. Research is inconclusive about which institutional attributes precisely matter in adaptation situations. Second, even less confidence exists about the many ways how specific institutional attributes shape adaptation decision-making and performance."
>
> (Oberlack, 2017, p.806)

Ensuring local authorities make appropriate and relevant climate adaptation decisions remains a global challenge (Collier et al., 2014). Interest in the challenges and barriers to climate decision-making has grown in light of recent research from the likes of Biesbroek et al. (2013), Lourenço et al. (2014) Moser & Ekstrom (2010) and Street et al. (2019). These contributions have identified a number of barriers impeding adaptation, however, have also stressed the need for practice-orientated research on 'real-world' adaptation decision-making to delve deeper and explore the systemic causes and causal relationships between influences on adaptation decision-making (Biesbroek et al., 2015; Eisenack et al., 2014; Lehmann et al., 2015).

This chapter contributes to this debate through an empirical study of the application of climate adaptation decision-making in practice, in the context of GCC. This chapter addresses Objective 1 by identifying and exploring influences on decision-making in practice at the city-level in Glasgow. It is recognised that the topic of barriers to adaptation is a crowded space with a large number of publications on the topic (Barnett et al., 2015b; Biesbroek et al., 2013; Bisaro et al., 2018; Eisenack et al., 2014; Moser & Ekstrom, 2010b). The novelty of this research derives from the detailed, longitudinal data collection, the framework used to analyse findings and explore interactions between identified challenges, and the claims resulting from analysis.

To achieve research Objective One, this chapter presents research on the decision-making processes of two different initiatives, the Glasgow Resilience Strategy (GRS) and Glasgow Climate Adaptation Strategy & Action Plan. Research initially followed the development and decision-making processes of Glasgow's Resilience Strategy. The Resilience Strategy, however, despite originally predicated on climate resilience, did not have a significant focus on climate in the end due to stakeholder preferences to focus on broader social issues such as inequality. As such, GCC subsequently decided to develop a climate adaptation strategy and action plan, which was therefore also studied, as part of this thesis. Action research took place between October 2015 and February 2020, consisting of 200 hours of observation, 27 semi-structured interviews with 38 stakeholders and regular meetings with the adaptation lead[19]. (A full record of all action research activities available in Appendix I.) Researching decision-making of both strategies provided the benefits of rich contextual understanding, relationship development and pattern recognition as well as enabling comparison and deeper reflection.

The chapter is structured as follows. Firstly, the context surrounding the development of the GRS and the Glasgow Climate Adaptation Strategy and Action Plan are introduced respectively (Section 6.1). Then a summary of data collection approach is provided (Section 6.2), followed by an introduction to the Context, Content and Process (CCP) Framework used to analyse collected data (Section 6.3). The framework is then applied and findings from action research are presented in relation to the themes of context, content, and process (Section 6.4). Analysis of the findings informs a discussion on challenges limiting decision-making (Section 6.5). Key points are then summarised to conclude this chapter (Section 6.6).

## 6.1 Glasgow Resilience Strategy and Climate Adaptation Strategy & Action Plan

Research was undertaken in Glasgow, UK. A full description of Glasgow and Glasgow City Council is provided in Section 4.3.1. This research followed the decision-making processes used to identify and appraise actions for two strategies in Glasgow City

[19] The "adaptation lead" was a civil servant employed by GCC who was in charge of the climate adaptation work strand and was the main decision maker.

Council, the Glasgow Resilience Strategy and the Glasgow Climate Adaptation Strategy and Action Plan. Both are briefly summarised here.

In 2013, Glasgow was selected as a participating city in the 'Rockefeller Foundation 100 Resilient Cities Initiative'[20]. The prestigious initiative aimed to select one hundred cities around the world to provide technical support [21] to become 'resilient[22]'. At the time of the 100RC's inception, GCC was initiating work to prepare for the effects of climate change, as a result of experiences of adverse weather events[23]. The main motivation for GCC to apply was thus to contribute to and build upon the ongoing climate adaptation work at the city and city-region scale. After being selected by the Rockefeller Foundation 100RC to participate in the programme, GCC were provided with funding from 100RC to (i) appoint a Chief Resilience Officer (CRO) which was set up as a leadership position within GCC to spearhead resilience work; (ii) commit to developing a resilience strategy for the city; and (iii) allow knowledge exchange with other selected cities around the world.

The 100RC programme provided prescriptive steps, tools and resources for cities to follow to develop their resilience strategies (Mart et al., 2018). The overall process was comprised of two main phases. Phase 1 consisted of developing a Preliminary Resilience Assessment (PRA). The PRA was required by 100RC to: (i) understand the city's current strengths and weaknesses in relation to potential disruptive shocks and stresses; (ii) outline existing resilience work; and (iii) facilitate discussion about what should be included in the resilience strategy (GCC, 2016b). Stakeholder engagement and consultation was a key part of this phase. Phase Two focused on opportunity identification, appraisal, and selection to choose actions for the Resilience Strategy.

[20] The Rockefeller Foundation is a large philanthropic body, with the mission since 1913 being to 'promote the well-being of humanity throughout the world' (Rockefeller Foundation, 2019). In 2013, to mark its centenary the organisation decided to establish a new initiative called the 100 Resilient Cities (100RC) to support urban resilience.
[21] Technical support included guidance resources provided by 100RC, personnel support from 100RC staff and provision of services from platform providers (Rockefeller Foundation 2019).
[22] Urban resilience is defined by the Resilient Cities Network (formerly 100RC) as "the capacity of a city's systems, businesses, institutions, communities, and individuals to survive, adapt, and grow, no matter what chronic stresses and acute shocks they experience" (Resilient Cities Network, 2020)
[23] GCC had also begun speaking to neighbouring local authorities about how they could collectively pool their knowledge and resources to build resilience to climate change at the city-region level. This later lead to the establishment of Climate Ready Clyde, a regional climate change partnership.

The final Resilience Strategy was structured around ‘pillars’ or core tenants of what was deemed to be essential dimensions of urban resilience in Glasgow (according to stakeholders). The four pillars of the resilience strategy were: (i) Empowering Glaswegians; (ii) Unlocking Place Based Solutions; (iii) Innovating for Fair Economic Growth; and (iv) Fostering Civic Participation (GCC, 2016a). These pillars were identified through community consultation, stakeholder workshops and steering group discussions. The Resilient Glasgow Strategy was launched in September 2016[24].

Despite the original 100RC application focusing on climate adaptation, the final Resilience Strategy had minimal acknowledgement of climate change and limited actions focusing on climate resilience. This shift in focus resulted from stakeholder feedback and prioritisation, which did not identify climate change as one the most significant threats perceived to affect the city’s resilience. The aim therefore altered from developing a climate resilience focused strategy, instead to a strategy where climate considerations were minorly mainstreamed across sectors and identified pillars.

In Autumn 2016, as a result of the Glasgow Resilience Strategy not featuring significant climate action, GCC decided to develop a stand-alone climate adaptation strategy and action plan. GCC’s intention was to create a strategic, city wide, adaptation strategy and action plan focused on increasing resilience through collaborative working that would run over a five-year period. There was desire from GCC that the outputs would not be owned solely by the city council, but action would be city wide and as such engaged with arm’s length organisations such as City Building Glasgow, academic institutions such as University of Strathclyde and University of Glasgow and private sector companies such as Network Rail, via a newly established Adaptation Task Force[25].

[24] At this point, the funding from 100RC stopped due to the end of the funding period (however expectation of deliverables from 100RC on Glasgow’s continued progress continued). In 2019, the Rockefeller Foundation discontinued the formal 100RC initiative. Whilst participating cities could continue to implement their resilience strategies, there was no longer support or resource from the Rockefeller Foundation. To maintain continued resilience efforts, GCC attempted to integrate resilience into business as usual within GCC and extended funding to the position of CRO.

[25] To enable the development of the adaptation strategy, an ‘Adaptation Task force’ was created in December 2016. The Task Force was set up to lead the development of a strategic climate adaptation programme by building evidence and bringing stakeholders together to identify actions underway, priority areas to address and propose new activities. Membership included representation from various departments in the city council, local education

The work programme adopted by GCC to develop the climate adaptation strategy and action plan was heavily influenced by Adaptation Scotland's cyclical risk-based approach to adaptation planning titled '5 Steps to Managing your Climate Risks', a Scottish version of the Adaptation Wizard described in Section 3.1 (Adaptation Scotland, 2013)[26]. The methodology was comprised of a multistage process of: (i) defining the challenge; (ii) assessing the threats and opportunities; (iii) assessing the climate risks and identifying actions; (iv) reporting and implementing; and finally (v) monitoring and reviewing. Research and engagement to develop the climate adaptation strategy and action plan occurred from 2016 onwards. Activities included climate impacts identification workshops with stakeholders, completion of a Local Climate Impact Profile (LCLIP) a desk-based climate change risk assessment and workshops to identify and appraise actions for the strategy and action plan.

Later, in 2019, GCC declared a 'Climate and Ecological Emergency'. A cross-party climate emergency working group was established to identify a range of recommendations for GCC to take forward. This resulted in a pause in the adaptation work and the informal disestablishment of the Adaptation Taskforce due to the new focus on Climate Emergency response. A Climate Emergency Action and Implementation Plan was released in Spring 2021 with a primary focus on mitigation. At the time of writing (February 2022) the Adaptation Strategy and Action plan was not yet approved by the council, already four years after the intended time of completion. This chapter identifies some reasons for this delay and explores the influences on climate adaptation decision-making, both in the resilience and adaptation strategies during the period of study.

Figure 6.1 and Figure 6.2 summarise the steps involved in the development of the Glasgow Resilience Strategy and Glasgow Climate Adaptation Strategy respectively. Activities undertaken by GCC and partners as well as my action research engagement are illustrated. It is highlighted that data collection stopped in February 2020. After my

institutes including the University of Strathclyde, University of Glasgow, and Glasgow Caledonian University (including members from both the estates and academic sectors). One council officer presided over this task group, referred to as the 'adaptation lead' for the remainder of this thesis.

[26] The method of which is similar to existing trends and tools such as the EU Adaptation Support tool and the UKCIP Adaptation Wizard, as detailed in Chapter 2.

PhD research data collection concluded, I maintained a professional relationship with GCC via my practitioner role at Sniffer, working on the Adaptation Scotland programme.

I recognised that substantial continued work on resilience and adaptation has occurred since the completion of my data collection, particularly in relation to Glasgow hosting COP26. I have observed this as I was asked to review GCC's climate adaptation plan, which was drafted in January 2022 with the intention to send to committee for approval in March 2022. In addition, I have provided support in my professional role since 2020, including providing training sessions on adaptation to project officers and managers and I supported the organisation to benchmark their adaptation progress (using Adaptation Scotland's Adaptation Capability Framework). The following section details PhD research data collection.

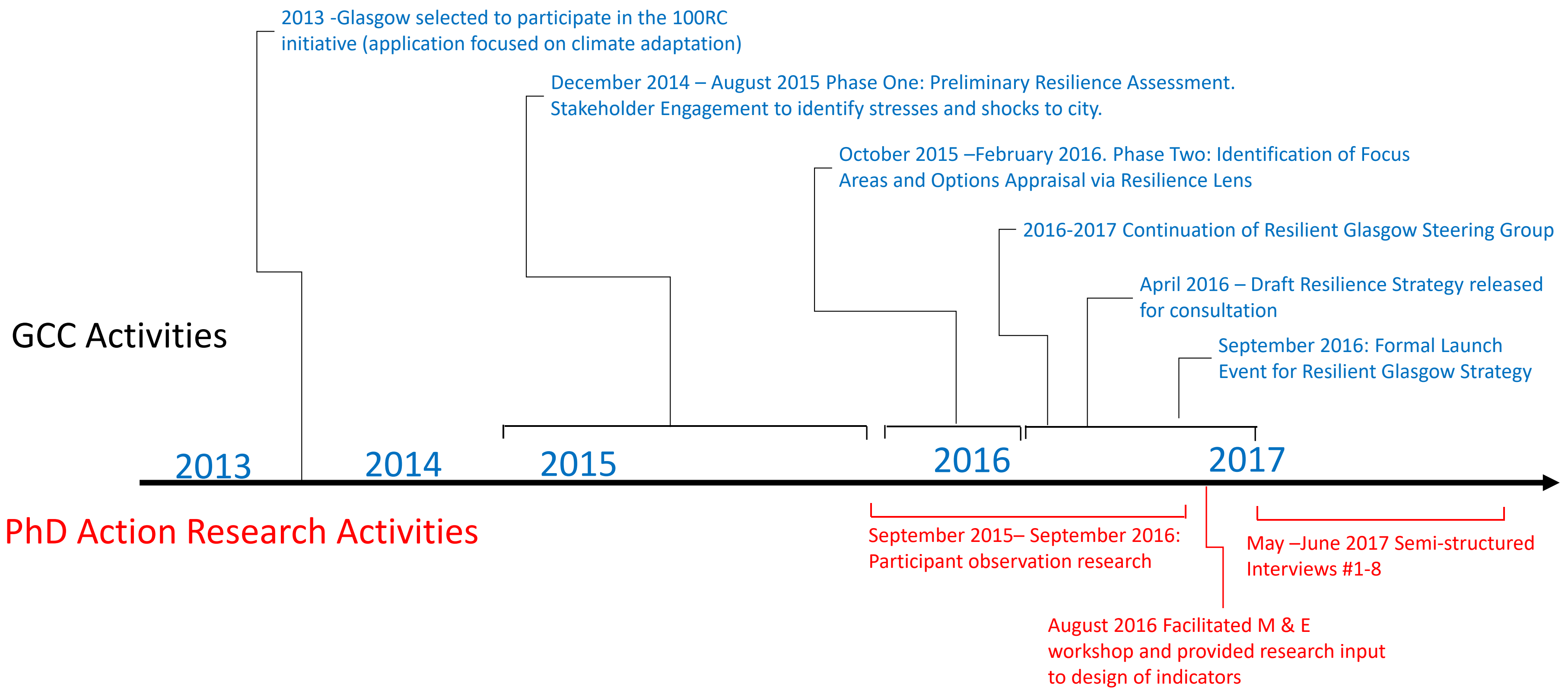



*Figure 6.1: Summary of GCC activities and my PhD action research activities in relation to the Glasgow Resilience Strategy (GCC, 2016)*

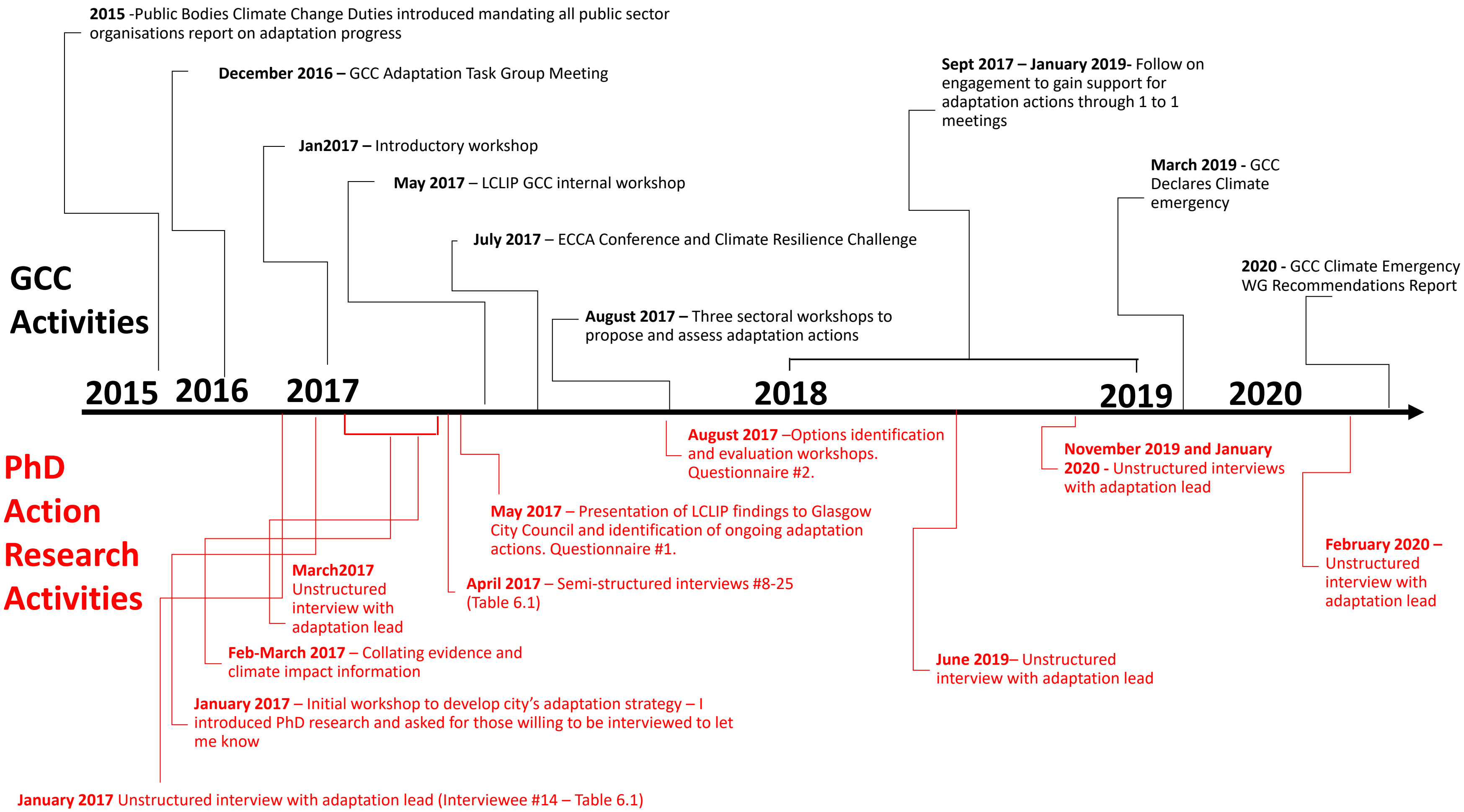



*Figure 6.2: Summary of GCC activities and my PhD research activities in relation to the Adaptation Strategy and Action Plan*

## 6.2 Data Collection

As this research was driven by an interest in exploring complex, real-world problems to understand influences on decision-making, the combined use of multiple methods was used to create a richer and more nuanced exploration, as described in Section 5.1. Research on the Glasgow Resilience Strategy included: (i) 75 hours of observations between September 2015 and September 2016 on the various resilience strategy development processes; (ii) attending 5 steering group and 6 working group meetings and 12 workshops; and (iii) 7 semi-structured interviews.

To study the development of the climate adaptation strategy and action plan, a total of 125 hours of action research was undertaken between September 2016 and February 2020 on the various climate adaptation strategy and action plan development processes. This involved (i) attending 8 task group meetings and 12 events and workshops; (ii) conducting 18 semi-structured interviews (outlined in further detail in Table 6.1) and unstructured interviews with the adaptation lead (the decision-maker) during 2016-2020; (iii) two questionnaires were used to collect data. One questionnaire was distributed at an internal GCC adaptation workshop in May 2017, referred to as questionnaire #1, and the second at three Climate Resilient Glasgow workshops in August 2017, referred to as questionnaire #2 (available in Appendix V). A summary of action research activities is also available in the Appendix I. A summary of the interviews undertaken is presented in Table 6.1.

*Table 6.1: Summary of semi-structured interviews undertaken to address Research Objective One*

| Interview Ref | Organisation | Representative and number of interviewees | Interview question themes (Full question set available in Appendix II and III) |
|---|---|---|---|
| Overview of stakeholder interviews conducted when evaluating the Glasgow Resilience Strategy | | | |
| 1 | GCC | GCC Resilient Glasgow Leads (n=2) | • The 100RC Application Process<br>• Resilience Work Governance – working groups, steering groups<br>• Engagement – what stakeholders were involved and how<br>• How stakeholders' inputs and resilience actions were identified and prioritized |
| 2 | | GCC Chief Resilience Officer (n=1) | |
| 3 | | GCC Resilient Emergency Response Team (n=2) | |
| 4 | Universities | University of Strathclyde Representative on Resilient Glasgow Steering Group (n=1) | |
| 5 | Third sector | Sniffer – Adaptation Scotland Manager –co-author of GCC 100RC applications (n=1) | |
| 6 | Emergency Services | Scottish Fire and Rescue (n=1) | |
| 7 | Consultancies | ARUP Project Partner (n=1) | |
| Overview of stakeholder interviews conducted when evaluating the Glasgow Adaptation Strategy | | | |
| 8 | GCC | Education Services (n=1) | • How have departments/organisations have been affected by extreme weather events to date<br>• How climate change affects departments or organisations strategic goals<br>• How climate impacts are monitored and reported<br>• What characteristics of the organisations enabled it to cope with previous adverse weather events?<br>• What measures are currently in place to deal with adverse weather?<br>• How are adaptation decisions currently made? How are various adaptation options considered and compared?<br>• What decision support tools or methods are utilised?<br>• What information is currently consulted when making climate resilience decisions?<br>• What attributes would you want in a decision support system for climate resilience? |
| 9 | | Carbon Management (n=1) | |
| 10 | | Winter Maintenance (n=1) | |
| 11 | | Transport Planning (n=2) | |
| 12 | | Resilient Emergency Response(n=1) | |
| 13 | | MGDSP (n=1) | |
| 14 | | Sustainable Glasgow – Climate adaptation (n=1) *Multiple informal interviews taken with this interviewee given their key role | |
| 15 | GCC Arm's Length Organisations (ALEO) | City Building Glasgow (n=1) | |
| 16 | | Glasgow City Marketing Bureau (n=1) | |
| 17 | Universities | University of Strathclyde (estates) (n=2) | |
| 18 | | Glasgow Caledonian University (estates) (n=3) | |
| 19 | Charities | Central Scotland Green Network Trust (CSGNT) (n=1) | |
| 20 | | Glasgow Clyde Valley Green Network (GCVN) (n=1) | |
| 21 | Utility Providers | SP Energy Networks (n=1) | |
| 22 | Public Bodies | Scottish Natural Heritage (now NatureScot) (n=1) | |
| 23 | | Transport Scotland (n=1) | |
| 24 | | Police Scotland (n=4) | |
| 25 | Community Groups | South Seeds (n=2) | |

To assess the generalisability of findings from Glasgow, additional interviews with adaptation practitioners and decision-makers from other cities were undertaken following analysis. These interviews and associated learnings are described in Section 6.4.5. Table 6.2 summarises the semi-structured interviews were undertaken with practitioners involved in adaptation decision-making in Northern Ireland (n=1) and the Netherlands (n=2).

*Table 6.2: Validation interviews*

| Interview Ref | Organisation | Representative and number of interviewees | Interview question themes (Full question set available in Appendix VI) |
|---|---|---|---|
| Overview of stakeholder interviews conducted when validating research findings | | | |
| 26* (continued from Table 6.1) | Climate Adaptation Services (CAS) | (n=2) | 1.Could you please describe the external context that influences adaptation within local authorities in the Netherlands / Northern Ireland (e.g., national policy, funding, citizen pressure etc.)?<br>2.What internal characteristics of local authorities affect adaptation (e.g., organisational structure, power dynamics, history, senior management, political landscape etc.)?<br>3.Is there a common approach to adaptation planning in cities in your country (e.g., Adaptation Wizard, RESIN Framework etc.)?<br>4.What data and evidence are used to inform adaptation planning and decision-making?<br>5.How are adaptation options typically identified and prioritised?<br>6.Are decision support tools used to aid options identification, prioritisation, and selection? If so what, tools/methods? |
| 27 | Climate Northern Ireland | (n=1) | |

## 6.3 Framework for analysis

As outlined above, this chapter addresses research Objective 1 which was to identify the challenges influencing current adaptation decision-making within the real-world context of a city council developing an adaptation strategy and action plan. There has been much debate in the adaptation literature as to what is meant by challenges or barriers. Multiple terms are used (often interchangeably) in the literature to represent things that negatively affect climate adaptation. For instance, Biesbroek et al. (2009) interpret constraints as obstacles which limit an institution’s ability to develop and implement adaptation actions. Moser & Ekstrom (2010) interpret barriers as obstacles which make adaptation less efficient and/or effective or associated with missed opportunities and/or increased costs. A third and commonly applied definition was proposed by Eisenack et al. (2014, p.868) who define a barrier of adaptation as "(1) an impediment (2) to specified adaptations (3) for specified actors in their given context that (4) arise from a condition or set of conditions. A barrier can be (5) valued differently by different actors and (6) can, in principle, be reduced or overcome."

Biesbroek et al. (2015) criticise studying barriers to adaptation, suggesting that categorising items or processes as a barrier inappropriately limits their complexity and dynamic nature into simplified and static statements about what is wrong with adaptation presently (Biesbroek et al., 2015). Such simplification is seen to be overly reductionist and does not account for the need to explore causal processes responsible for specific outcomes or effectives (Biesbroek et al., 2015; Measham et al., 2011). My interpretation of challenges are obstacles or constraints which impede or limit adaptation. There has been a purposeful choice not to use the term barriers due to their contention and narrow focus in literature. This research is interested in exploring influences and causal mechanisms rather than pre-emptively identifying such influences as barriers. The exploration of influences also enables the identification of factors or processes which support adaptation decision-making and good practice to occur.

Thus, research sought to explore influences on adaptation decision-making. There are several frameworks pertaining to adaptation challenges or barriers more broadly (not just decision-making) (Moser & Ekstrom, 2010; Eisenack et al., 2014; Lehmann et al., 2015), however a framework from the organisational studies field was chosen to analyse and present the data collected. Climate adaptation necessitates changes occurring in institutions, however studies exploring how and why institutional change through decision-making are limited (Patterson et al., 2019). The justification for this methodological choice and how the selected framework for analysis relates to existing approaches and current debates within climate adaptation, is presented here.

This research adopted the Context, Content and Process (CCP) framework developed by Pettigrew (1990) to structure analysis and present findings. The CCP Framework explores: (i) the context in which the decision maker was operating, including national policy influences and organisational attributes; (ii) the process of decision-making and options evaluation including the guidance and steps used and decision support systems or lack thereof; and (iii) the content (the data and evidence) used (Pettigrew, 1990). The context is further demarcated into inner (the internal institutional influences) and outer (the external factors that may affect internal processes). These concepts and the relations between them are illustrated in Figure 6.3. Time is an element that cuts across all three categories, acknowledging that the context, content, and process will change over time, as shown in Figure 6.3.

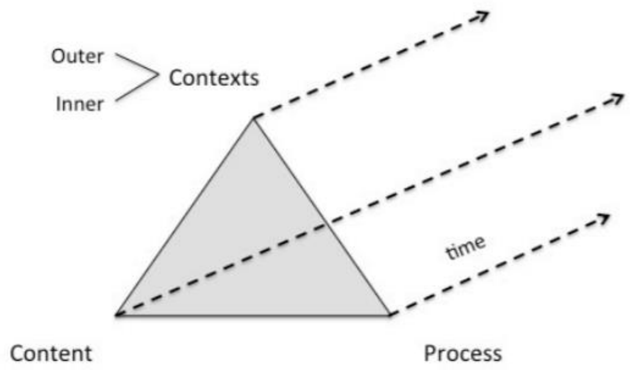



*Figure 6.3: Context, Content and Process Framework, otherwise referred to as the 'Pettigrew Triangle', which illustrates the three concepts of organisational change studied in this research. Source Pettigrew Lecture Slides (April 2009)*

The CCP framework takes a contextualist approach to change management by highlighting that change occurs within a historical, cultural, economic and political context (Iles & Sutherland, 2001). Given that climate adaptation is by its very nature, a form of change management, the transferability of the framework seemed favourable. Despite the age of the framework (it was originally published in 1990), it’s mid-level nature and relevance to current adaptation literature, made it appropriate for use in this research.

Other frameworks do exist to explore organisational dimensions of adaptation. Examples include  Oberlack and Neumarker (2013) which adapted Ostrom’s Institutional Analysis and Development (IAD) framework (Ostrom, 2009) and applied it to climate adaptation with the inclusion of context and process variables. The CCP framework, however, also enables the categorisation of barriers previously identified in the adaptation literature. For instance, Moser & Ekstrom's (2010) framework to diagnose barriers also highlights the importance of process and context to adaptation, as well as the role of actors. Within this thesis, actors are not considered separately but within the context, content, and process in relation to decision-making. In addition, Lehmann et al. (2015) assessed barriers and opportunities for effective adaptation planning in cities and proposed a two-tier framework of variables influencing decision-making, with emphasis on the interaction between such influences, similar to the CCP interactions.

Current frameworks to explore adaptation, however, typically identify institutional variables relevant to adaptation, but are less detailed about the (assumed) interactions of the variables (Oberlack, 2017). Dupuis and Biesbroek (2013) stress the need to explore the effect of variables on adaptation outcomes. Oberlack (2017) also call for further research on precise conditions relating to attribute detection (highlighting what characteristics enable or restrict adaptation) and a broader, more holistic examination of attributes. The CCP was selected due to its mid-level nature, meaning that analysis was informed by action research rather than pre-defined categories and that content, or information used within decision-making was part of the CCP and not other comparable frameworks.

The CCP Framework was thus selected for use in this thesis, to structure and analyse findings. The CCP framework is classificatory and organises variables which shape adaptation decision-making and partitions them into factors relating to context, content, and process separately before exploring the relationships. The CCP framework was selected for three key reasons. These reasons include:

**Data alignment:** Firstly, the thematic areas identified from the data collected were clearly aligned with the CCP. The initial thematic analysis assessment highlighted the importance of the wider environment, data and evidence and decision-making processes as key topics emerging from the collected data. Given that this research is centred around a public sector organisation (GCC) utilising a new process, involving complex content, and adapting to both internal and external pressures (context), the CCP framework appeared appropriate.

**Appropriate scale:** The CCP is a mid-level framework which is not overly prescriptive and therefore allows the researcher flexibility to adapt the framework to suit the object and scale of research. The CCP framework offers a valuable and complimentary structure with which to analyse and communicate the findings.

**Helps identify root causes of challenges:** There is a need to examine the drivers of challenges or barriers for adaptation. The CCP framework helps the research shed light on systemic drivers and aligns with Biesbroek et al.'s (2013) call to delve deeper into adaptation barriers and enablers to explore how they originate and interact.

Whilst there are numerous definitions of limits, constraints, challenges and barriers (to adaptation) arising in the literature, criticism comes from the lack of evaluation of interactions between barriers and limited examination of the root causes of barriers (Biesbroek et al., 2013; Lehmann et al., 2015). Biesbroek et al. (2013) argues that too often studies have been predicated on "asking the questions 'if' and 'which' barriers exist" rather than to "begin asking 'how' and 'why' barriers emerge". Multiple studies have focused on describing barriers or constraints as opposed to unpacking their drivers, roots and possible impacts (Gawith & Hodge, 2018). Often one dimensional lists of barriers are proposed by researchers (Füssel, 2007b; Adger & Barnett, 2009; Biesbroek et al., 2011; Measham et al., 2011). The CCP framework enables the examination of challenges from multiple angles (context, content, process, and time) building on the two tiered approached of Lehmann et al. (2015) to explore interactions between identified influences.

Studies suggest that different barriers cannot and should not be understood or explored individually in isolation. Many of these barriers are interrelated. Barriers may occur simultaneously or re-enforce one another and thus must be acknowledged. Eisenack et al. (2014, p.869) state "we argue that understanding the interdependencies of barriers is central for explaining their occurrence, persistence and resolution." In addition, Eisenack et al. (2014) suggests the need for barriers to consider dynamic changes, as opposed to being static snapshots of barriers at a certain time. The importance of adopting a dynamic perspective including exploration of causal relationships between barriers was stressed. For instance, long term austerity leading to financial limitations can lead to or exacerbate other barriers such as lack of information, coordination, or human resource. Simplistic interpretations or lists of barriers are often static and do not acknowledge the role of time. A particular value of using the framework is to assess the interconnectedness between the three attributes of the CCP – in a sense the overlap of the attributes as it is the connections between CCP factors where the key barriers and potential for solutions lie.

As has been outlined, the CCP framework examines the why of change (context), the what of change (content) and the how of change (process) (Stetler et al., 2007). The advantages of the CCP approach, such as exploring dynamic relationships between factors and being generalisable enough to be applied across domains, have been illustrated via wide ranging applications. For example, the CCP Framework has been used widely in practice across diverse sectors including patient care and service delivery in health care systems (Stetler et al., 2007), employees' openness to change (Devos et al., 2007), political marketing strategy (Baines & Lynch, 2005) and to analyse and learn retrospectively from change programmes in organisations (Iles & Sutherland, 2001).

Users of the CCP framework, however, interpret each attribute in slightly different ways to suit their object of research. Given the variance in interpretations of these terms, definitions used within this study are summarised in Table6.38. The remainder of this chapter presents the findings of the research with respect to the three factors of content, context, and process. To clarify scope, this research investigates the environment within which decision-making occurs, and the data and process used, rather than focusing on the specific adaptation options or outcomes of decision-making.

*Table 6.3: Context, Content and Process Definitions in Study*

| Term | Interpretation of term used within this Study |
|---|---|
| Context | Context is categorised into external and internal. External context refers to all influences that were exerted from outwith the organisation, whilst internal relates to the contextual characteristics within an organisation. Types of external contexts include the likes of national policy, technological change and industrial developments, whilst internal context relates to organisational structure, power dynamics and distribution and historical performance (Bell et al.,1997), senior management characteristics (Shepherd & Rudd, 2014) or changing political environment (Kuipers et al., 2014). In GCC, key influences of context externally were changing policy requirements and citizen pressure, with internal context being influenced by limitations in awareness of adaptation and leadership. |
| Content | According to Bell et al., (1997) "content refers to the substance of the choice". Content represents the topic of the decision to be made. Within this study, content refers to the type of adaptation actions being considered and the data and evidence on which they are based. Content is therefore viewed as the information, evidence and actions that were evaluated as part of the adaptation planning and decision-making process. The key influences of content from GCC study were lack of economic data, poor data collection and vagueness of proposed actions. |
| Process | Process within this study, refers to the steps undertaken for decision-making, including options identification, prioritisation, evaluation, and selection. The key influences of process in GCC were siloed options identification, lack of evaluation and biased prioritization. |

## 6.4 Findings

This section presents the research findings produced through analysing the data collected via the CCP framework. To analyse the data collected, thematic analysis was undertaken (as detailed in Section 5.1) using the CCP framework. Analysis was completed by reviewing notes from field notebooks, relevant meeting minutes, publications, and the interview notes together. Findings were grouped into the categories of the context in which decision-making occurred, the data and evidence used and the process of decision-making. This section provides an outline and discussion on content, context and process influences with regards to the development of Glasgow's Resilience Strategy and Climate Adaptation Strategy & Action Plan. It explores each element of the CCP individually, before exploring the interconnections between the influences collectively.

### 6.4.1 Context: the environment in which decision-making occurs

The following section describes the context in which decision-making occurred. Organisations do not make climate adaptation decisions within a vacuum but within a broader institutional environment influenced by structures, capabilities, resource and competing priorities. The CPP framework suggests that decision-making is both a social and political process (Pettigrew, 1990). Moser & Ekstrom's (2010) framework also highlights the role of governance systems in context. Similarly, Lehmann et al.'s (2015, p.78) framework defines the institutional environment or context as the ‘formal and informal rules guiding interactions between actors’.

Adaptation decision-making occurs within the broader policy making landscape, and can therefore be influenced by competing priorities, political and institutional structures, and decision-making schedules. Thus, it is important to consider the context in which decision processes occur. Context is categorised into external and internal. External context refers to all influences that were exerted from outwith GCC, whilst internal relates to the contextual characteristics within GCC.

A questionnaire on challenges to adaptation was issued at a GCC Adaptation workshop in May 2017 (see Section 5.1 and Figure 6.4). The results of this questionnaire identified perceived challenges to adaptation. Factors that were identified as major or moderate challenges to GCC’s adaptation included (i) securing funding for adaptation, (ii) gaining buy-in from other departments and senior management and (iii) accessing climate information, obtaining sufficient and accurate scientific data, as demonstrated in Figure 6.4. Following this, a second questionnaire distributed at the three Climate Resilient Glasgow workshops with GCC and external organisations present. Questionnaire #2 also posed questions relating to what respondents believed was the main barrier to adaptation in the Glasgow city context. The most commonly cited challenge was leadership, including political support from both national and city government levels. The findings from these questionnaires ae further explored in the following sections.

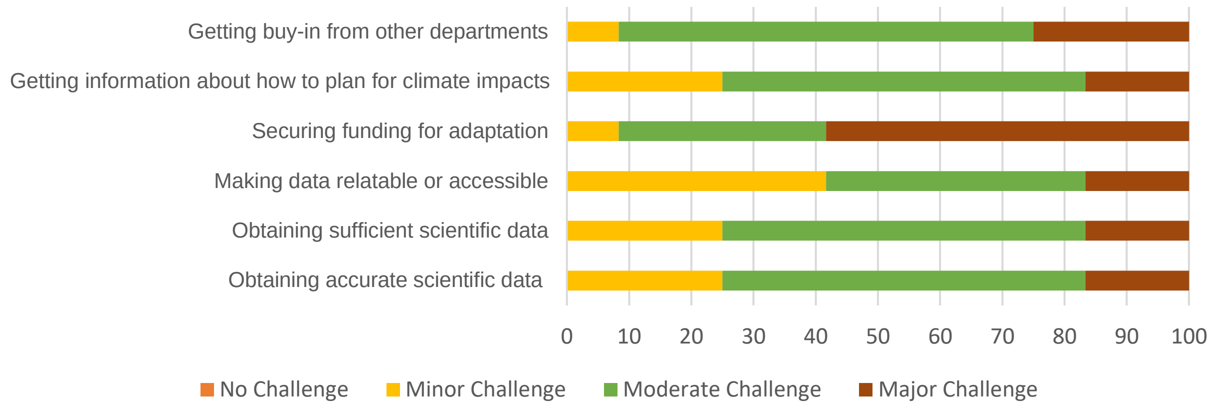



*Figure 6.4: Graph of survey response assessing challenges to address climate impacts or promote climate adaptation in GCC (n=12)*

### *6.4.1.1* External and internal context: lack of resource

In addition to the questionnaire responses, analysis of the observation notes and interview data, it was found that the most identified and discussed contextual factor was lack of resource available for adaptation and climate resilience. Questionnaire #1 with GCC staff revealed that funding was perceived as the most challenging aspect restricting adaptation, as nearly 60% of respondents categorised it as a major challenge. Resource limitations for adaptation were not limited to within GCC. The results from questionnaire #2, distributed at the Climate Resilient Glasgow Workshops, revealed that a third of all respondents felt funding and resourcing was the main barrier to adaptation in their own organisation and/or the wider city.

Responses indicated a belief amongst GCC staff that lack of resource was restricting adaptation planning and implementation across multiple levels. For example, interview #11 highlighted that the resource constraints result from the current state of national finances, not just the councils. In addition, interviewee #24 stated, “any business is juggling priorities, in an ideal world, we would be working on it [adaptation], but [we] need to think about resources (in terms of both people capital) and how to prioritise, which can be tough”. This element of human resources, as well as financial, was found to be important. For instance, the resilient emergency response team in the council was downsized from 6 to 2 following the economic crash, despite a need to respond to an increasing number of critical incidents. Similarly, interviewee #13 commented, “a big barrier is pulling together a business case to justify any intervention at all”.

Lack of sufficient funding impeded the adaptation strategy and action plan development. For example, according to GCC's adaptation lead, the Adaptation Taskforce 'faded away' in 2018 due to competing financial priorities and lack of resource within GCC. Financial barriers were also highlighted by interviewee #15, who reflected on adaptation needs within their own GCC department stating, "the cost [of adaptation] even though it's small is a barrier". It was felt however by interviewees that appropriate funding and investment were needed for to Glasgow become a 'climate resilient city'.

Financial resource limitations not only restrict adaptation but also influence the type of adaptation pursued and potentially increase incentives for maladaptation (Eisenack et al., 2014). For example, the tendency for local authorities to prioritise capital over maintenance spend was cited by interviews #9 and #11 as influencing adaptation by favouring hard defences over soft approaches as funding for on-going maintenance was hard to find or secure. Limited funding thus altered which adaptation options are identified and included within decision-making processes. Interviewee #8 stated "a barrier to action is the inability to undertake climate actions, that may be needed, but are not financially sound". Interviewee #15 reflected "it's hard to be proactive, because everything is dictated by cost…the priority is budget, and the environment is second string to that." Interviewee #13 also stated there was a need for increased resourcing as well as alternative assessments of business cases (extending beyond cost benefit).

Questionnaire #2 responses showed that a third of respondents felt that the main objective for the department or organisation was to save money and would be interested in adaptation if it resulted in cost saving. Interview #3 reflected on resource constraints also being a motivator for work on the resilience strategy saying, "if this [the Glasgow Resilience Strategy] joins up approaches and helps us deliver what we already wanted to deliver in a more effective and lean way they we are on to a winner, especially during time of austerity". There therefore appeared to be a preference for and focus on cost savings (potentially greater than the interest in what activity was most needed or appropriate).

Temporal constraints were found to interact with resource constraints. The council budget is tied to a four-year political cycle, shortening the time frame available for prioritised actions. In addition, the implications of austerity since the 2008 financial crash restricted budgets for public bodies across Scotland, putting an emphasis on short-term solutions to achieve balanced budgets and hampering an organisation's ability to fund long-term large scale initiatives (Hastings et al., 2015). The timeframe of climate adaptation decision-making should ideally consider long-time scales, as the effects of climate change are locked in for at least one generation to come and projects may have long term consequences and costs (such as maintenance) (Jones et al., 2014). Developing effective long-term responses under uncertainty can thus be difficult because of short term political and funding decision-making cycles. For instance, a new piece of infrastructure such as a bridge may be influenced by a four year political decision-making cycle but may exist for 100+ years (Smith et al., 2011).

Similarly, there was of lack of resource in relation to time allocated. It was positive that there was recognition enough of adaptation, for it to be part of a staff member's formal role (but not job title). However, adaptation was seen to warrant the resource of a full-time position or multiple positions, which it was not given in practice. The adaptation lead was also repeatedly pulled away from adaptation to work on other higher priority areas. Furthermore, adaptation work was often given tight timeframes in which to deliver draft strategies or action plans, which were then not progressed within the council.

Findings suggest that the root cause of limited resource may derive (in part) from collective lack of awareness on the need to adapt. Ekstrom & Moser (2014) found that lack of resource can derive from institutional or behaviour cultures influencing buy-in. Observation research and interview findings for this research observed this, particularly the organisational preference for mitigation over adaptation. Siloed working, the manner in which mitigation and adaptation were treated by GCC during study, may also limit awareness and thus relevant funding. The following section explores the lack of awareness and buy-in for adaptation in GCC.

*6.4.1.2* Internal context: lack of awareness and buy-in

Collected data indicated that awareness was an issue impeding adaptation progress within GCC. For instance, gaining buy-in was identified via questionnaire responses as the second most challenging aspect to adaptation in the organisation. Questionnaire #1 responses highlighted challenges associated with the lack of awareness of the impacts of climate change, limited understanding of consequences and lack of incentives to build adaptation responses. The idea that there was a need for incentives for adaptation action, illustrates climate impacts were not perceived as sufficient drivers, in their own right. Interviewee #9 stated “there is a lack of awareness of the impacts of climate change but also a lack of incentives to build adaptation response”. Comments from interview #16 highlighted that the main constraint to adaptation was that people don’t know about how the climate will change for Glasgow. Interviewee #12 stated, “There’s a behaviour element to be overcome, rather than just the cost. There is definitely a lack of understanding and different priorities …if I went up to the executive board next week to try and explain resilience, I don’t think they would actually know what it’s all about…they would only be receptive to the conversation if there is potential of punitive measures. This is possible a lack of leadership – driven by a lack of knowledge or understanding.”

This institutional lack of awareness was cited in multiple interviews. Interview #21 cited organisational challenges with buy-in, stating “there are attitudinal barriers, as not everybody is bought into the idea of climate change and therefore the need to adapt to it…climate change is a challenge as it’s everyone’s responsibility and nobody’s at same time”. Interviewee #13 noted that some GCC colleagues believed climate impacts were not a significant concern for GCC or the city or that sufficient work was already underway to address climate change. Both interpretations led to the view that adaptation was ‘not their problem’ and did not need to be addressed. Furthermore, they found council employees in a number of departments had limited understanding about how adaptation or climate change related to their work, despite significant capacity building efforts[27]. The skills, knowledge and competence of staff relating to

[27] A lot of work by the adaptation lead was undertaken to build awareness. There were multiple instances where the adaptation lead invested significant amount of time to build internal awareness to be able to initiate discussion and action. Examples range from introduction to adaptation and examples of adaptation actions at the May 2017 workshop through to recapping on adaptation at benchmarking workshops in February 2021. There was a constant need to remind colleagues of what adaptation was. Whilst this awareness raising was vital, it repeatedly held up activities.

climate change issues was thus seen as limited. Interviewee #14 said it feels like “it’s [climate adaptation] another thing we’ve got to do with lack of clarity on”. In addition, interview #14 stressed that whilst a few departments such as flood risk management and transportation are competent and active on adaptation, the topic is not yet mainstreamed across the organisation.

The demographic make-up of the organisation, however, was identified as an influence on awareness and buy-in within GCC. For instance, semi-structured interview #15 discussed cultural acceptance of climate change, stating “You see awareness of climate change more and more in younger employees, it’s definitely a generational thing…apprentices are more on board with it than the guys who have been here for 30 or 40 years”. Diversity of staff and experience of climate impacts were seen as advantageous for awareness of climate adaptation.

Awareness may have been limited due to lack of severe climate events and impact(s) affecting GCC to date. The threshold of concern or initial framing of climate adaptation is a common barrier to adaptation (Moser & Ekstrom, 2010a). For instance, the resilience strategy development process revealed that stakeholders did not perceive climate change to be a major concern. In addition, whilst climate change was on the GCC wide risk register, climate risk was not recognised on departmental registers or that of other public bodies, as noted by interview #23. Interviewee #20 stated “extreme weather and gradual climate change are two separate challenges”. This reflects the more common acceptance of emergency management responding to adverse weather incidents over adaptation planning processes.

A discussion point at multiple adaptation task force meetings was how to progress adaptation in the absence of a crisis. Most adaptation actions undertaken by GCC had been taken after or in response to an adverse event. For example, Glasgow did have severe floods in July 2002 (in the Sighthill area) which led to the formation of the Metropolitan Glasgow Strategic Drainage Partnership (MGDSP). This highlights the challenge of decision-making to address the ‘climate emergency’ as it was found stakeholders struggled to come to terms with this unique context in which the emergency unfolds in both the short term (through shocks) and long-term (through stresses and gradual changes).

Levels of awareness and buy-in did alter during the period of study. For instance, interview #25 stated, “I don’t know or understand how climate change will affect Glasgow directly”. However, when I conducted a survey of understanding within questionnaire #1, 70% of respondents reported their understanding was good (a score of 6 or above on a 1-10 scale). In terms of enablers raising awareness, the decision-maker highlighted that they perceived that the resilience agenda had catalysed political buy-in and momentum, which they hoped ‘added a certain level of weight to push the climate resilience agenda forward’[28].

Temporality was also seen to influence awareness and buy-in. A significant challenge to buy-in for adaptation was related to the challenge of time. It was noted by interviewee #14 that it is hard to get organisational buy-in for twenty years, not only because of short-term budgets but also the recognition that significant institutional memory is required to successfully implement and learn from a long-term adaptation programme. It was identified that leadership, however, can spur awareness and build long-term support.

*6.4.1.3* Internal context: lack of leadership

Leadership may arise from individual leaders, either via formal management positions or champions who push an agenda forward (however the extent of the influence of these individuals is closely related to administrative structures, party politics and

---

[28] The notion of resilience had traction briefly in the organisation and this influenced adaptation action. There was a strategic decision made by the adaptation lead initially to refer to adaptation activity as ‘Climate Resilient Glasgow’ (when it was initiated in 2017) however this terminology altered over the course of the study with the work stream later being referred to as climate adaptation, possibly reflecting the lack of momentum or impact achieved through the Resilient Glasgow Strategy. In addition, interviews (#1, 2 and 3) noted that multiple interpretations of the term ‘resilience’ also led to confusion. Another finding related to the role of external actors in raising awareness about particular issues. For instance, interviewee #2 commented that the ‘badge’ of the Rockefeller Foundation 100RC gave gravitas to pre-existing resilience efforts in a way which helped break down siloes, enable departments and individuals come together to progress resilience and add a deeper dimension to ongoing or planned work. Yet, this represented a double-edged sword effect, whereby when the 100RC programme was discontinued it led to limited follow up or review of any of the planned actions. Adaptation Scotland, a government funded programme, also provided support to GCC on the adaptation strategy and action plan development.

institutional capacity) (Bulkeley et al., 2011). As Wilbanks (2007, p.284) highlight a key factor for local agency on adaptation is "leadership at any and all scales, which is often the hidden factor in determining whether sustainability barriers are overcome and potentials are realised". Leadership is required for effective climate adaptation development and lack of leadership support from senior managers and elected officials can restrict or stall adaptation progress. Such leadership on adaptation, was found to be lacking in GCC, during the period of study.

Lack of leadership on adaptation and climate resilience in Glasgow was cited by multiple sources. Interviewee #14 highlighted that leadership was a barrier and stated, "I get so far and then you're stuck at officer level – [we] need senior enthusiasm and buy-in. This has slowed progress to date". In their experience, adaptation needed 'mavericks' operating at a high level. An example of ambitious leadership, that was cited for GCC was when the leader of GCC declared that they would become carbon neutral by 2030 publicly and then officers were tasked with achieving this. However, no such leadership was shown on adaptation via public commitments. Questionnaire (#2) respondents stressed the pivotal role leadership plays with 50% of responses identifying leadership as the most important contributing factor to Glasgow becoming a 'climate resilient city'. Written feedback to open ended questions cited a barrier for GCC as the need for "a cultural shift in order to aid implementation of coherent strategies. Adaptation requires changes in the way GCC operates and too many people are averse to changing patterns". Other responses also highlighted the need for consensus across levels of leadership and effective multi-level governance.

Leadership for climate adaptation in GCC was observed to vary throughout the period of study. There appeared to be differing commitment to adaptation action. For instance, adaptation was central to the 100RC application, this then waned due to stakeholder preferences via engagement. The council still pursued adaptation via committing to a strategy, however this was paused due to competing commitments and pressure to focus on low-carbon activities. Leadership was needed to legitimise the case for adaptation. Leadership changes, however, were found to alter progress, in this case positively. The Chief Resilience Officer changed when the strategy was released to another senior member of staff, who was very openly committed to adaptation (for instance was the GCC representative on the Climate Ready Clyde board).

In addition to challenges of leadership internally in the council, there were pressures relating to how the organisation was perceived externally. For instance, at a Glasgow Adaptation Taskforce meeting in June 2017, a conversation was had reflecting on the varied maturity of public bodies in relation to climate adaptation. NatureScot and Historic Environment Scotland were highlighted as further ahead (than GCC), as they had completed climate change risk assessments and made public commitment to adaptation action. Observations at this meeting captured a hesitancy of council staff to lead a city-wide adaptation programme when their ‘own house wasn’t in order’, particularly in comparison to other public bodies. At this meeting, comments were made on the need to consider a ‘softer’ and ‘less ambitious’ adaptation plan to build capacity and understanding to ‘get up to speed’ with other public sector organisations.

Influences were identified arising not only from leadership of senior civil servants within the council, but also elected officials. An interview with interviewee #14 in January 2020 revealed that positive political support (for climate adaptation) had appeared, however this had left the adaptation lead in a challenging position to commence strategy work again and revisit colleagues after such a long hiatus (approximately two years). In addition, interview #14 highlighted that a lever for enhancing leadership (in their organisation) was international exchanges and visits (for example, city exchanges with Pittsburgh, USA).  Many of these shifts in leadership were therefore influenced by external pressure (as described later in Section 6.4.1.4).

#### *6.4.1.4* External context: policy changes and citizen pressures

In addition to internal influences, there were a number of external factors affecting adaptation decision-making within GCC. Whilst this research is focused on GCC as an organisation, it is important to acknowledge the broader landscape in which it operates. This section therefore discusses external factors including policy developments and citizen pressure.

National policy and legislation are key contextual elements that influence city-level decision-making (Westerhoff et al., 2011). Policy developments which influenced GCC's climate adaptation work during the period of study were the introduction of Public Bodies Reporting Duties as part of the Climate Change (Scotland) Act in 2016 and the publication of the second Scotland Climate Change Adaptation Programme (SCCAP) in 2019.

SCCAP2 takes an outcomes-based approach to adaptation. This involved replacing the previous headings of Built Environment and Infrastructure, Natural Environment and Society and Economy (that comprised the structure of the previous SCCAP1) with seven holistic outcomes (Scottish Government, 2019b). The introduction of SCCAP2 and the outcome approach, led to delays in GCC's climate adaptation strategy and action plan development process because the adaptation lead had initially used SCCAP1's sectoral approach to structure engagement and content.

An outcomes approach to adaptation, as advocated for by SCCAP2, aims for adaptation to be addressed strategically and mainstreamed across all departments within an organisation. GCC expressed commitment to mainstream adaptation considerations across organisational departments. Attendees at multiple Climate Resilient Glasgow Taskforce meetings throughout 2017, stressed that climate adaptation could not be seen as solely an environmental issue or the responsibility of just the climate and environment team. Instead, it was felt by task group members, that adaptation requires cross-departmental contributions and coordination across both strategic and operational levels. The extent to which adaptation has actually been mainstreamed across GCC, however, has been minimal in published policies and plans. For instance, even the council's Climate Emergency Implementation Plan has only nine mentions of the word adaptation in the ninety-five-page document and only four of the sixty-one actions explicitly reference adaptation (GCC, 2021). Public bodies climate change reporting duties initially catalysed institutional commitment for adaptation. When it became clear that there were no rewards nor ramifications resulting from the submissions of reports, however, less gravity was given to the reporting process, according to interviewee #14.

Another national policy decision which had ramifications for GCC was the national declaration of a climate emergency by the First Minister of Scotland in April, 2019 (Scottish Government, 2019a). A month later, GCC declared a climate emergency as well. GCC's declaration of a climate emergency and outputs of the climate emergency working group were influenced not only by national actions but also by citizen opinion. Pressure from civil society groups and citizens were thus also an external influencing factor on the adaptation strategy. For example, interviewee #14 suggested that the Adaptation Strategy and Action Plan was significantly delayed as a result of Extinction Rebellion (XR)[29] activities in 2018. The group targeted local authorities across the nation, including GCC. As a result of their protests and direct action, GCC was forced to urgently establish a cross-party Working Group with representatives from civil society to explore the topic of Climate Emergency. Whilst this was advantageous in that it spurred cross party discussion, support, and the eventual declaration of a Climate Emergency, it directly detracted attention and resources away from adaptation. The adaptation lead was tasked with supporting the working group and drafting the Climate Emergency Plan halting ongoing adaptation work. These findings raise questions about the influence of citizen engagement on adaptation.

Community engagement and continual discourse is vital for climate resilience efforts, as was highlighted by interviewees (#1, 2 and 12). Glasgow's experience was indicative of increased pressure from civil society on public sector climate change action occurring across Europe, typified by Fridays for the Future school strikes and XR activities and highlights the importance of public participation in climate action (Hügel & Davies, 2020). The focus of citizens and lobbying groups has tended to be on mitigation, and this could, however, be to the detriment of adaptation efforts.

The role of city councils and budgets is also often heavily influenced by other levels of government. Interest and commitment to adaptation at national and regional levels also influences action at local level (Amundsen et al., 2010). Given the importance of regional influence I decided to research Climate Ready Clyde (CRC), the city region

[29] A climate activist group established across the UK in late 2018 to raise awareness of the urgency of climate change action in light of the IPCC's 1.5 degrees warming report which highlighted the critical period of reducing emissions before 2030

adaptation partnership (described in Section 4.3) and I undertook a social network analysis to explore how information and power was being shared amongst actors at different scales. This was not pursued further given lack of interest by CRC board members which was indicative of the lack of appreciation of academic research input to adaptation processes.

### 6.4.2 Content: the data and evidence used to inform decision-making

The second element of the CCP Framework is content. According to Bell et al. (1997) "content refers to the substance of the choice". Within this study, content refers to the type of information considered within the decision-making process, or the adaptation actions being considered and the data and evidence on which they are based. These aspects will be explored here collectively.

#### *6.4.2.1* Data and evidence used to inform adaptation options identification

In terms of the resilience strategy, the Glasgow Game was used to collect data. It was an interactive scenario planning game that used multiple perspectives in considering future outcomes, to engage stakeholders and gather data on local evidence of experienced shocks and stresses[30]. The game was used to gain a holistic understanding of the city's risks and identify opportunities for collaborative working. Through stakeholder interaction and input during the game, it was possible to identify and explore the 'shocks' and 'stresses' that participants perceived as most important for the city.

The responses from the workshops highlighted that, attendees were most concerned with broader social issues such as poverty and inequality, over climate change. This was further supported by the results of a later workshop with invited public, private and third sector organisations to prioritise the identified shocks and stresses. The feedback from stakeholders to focus on poverty and deprivation led to a shift away from climate

[30] The Glasgow Game was used by GCC through targeted workshops with specific groups, particularly those that were seen as hard to reach in normal policy consultations such as Third Sector Forums, Disability Alliance and Inter faith organisations. In total, 12 workshops with 9 stakeholder groups comprising over 300 participants were held to play the game. I attended three of these workshops as an observer.

adaptation as the sole focus of the resilience work. This illustrates a divide between data and evidence of climate impacts and public perception within this study.

Development of the climate adaptation strategy and action plan was initially premised on utilising information on climate risks to identify appropriate adaptation options. The adaptation strategy aimed to enhance resilience to the climate risks identified for Glasgow. According to documents provided at taskforce meetings, an aim of the work was to ensure “an evidence base including assessment of impacts, risks and vulnerabilities as well as well as identification of potential responses to be developed and communicated”. Climate risks were identified via the climate impacts workshop in January 2017, the findings of the LCLIP in May 2017 and a desk-based risk assessment process.

To identify and characterise climate impacts, one source of data and evidence used within the adaptation process was the results of the Local Climate Impact Profile (described in Section 5.1.2). LCLIPs are used widely by local authorities across the UK, including in Scotland[31], in order to understand how an organisation has been previously affected by adverse weather events. Findings on climate impact information in this study highlight two key challenges for content (or data and evidence)[32]. Firstly, that information is rarely recorded formally, and secondly that it is often not in a useable format.

This study revealed a lack of formal recording of climate impacts. Findings from the LCLIP indicated that evidence and information on experienced climate impacts was sparse as those departments and organisations contacted for quantitative information

[31] Aberdeen, West Lothian Council and Dundee City Councils all have published LCLIPs

[32] Given the important role GCC placed in the LCLIP as part of the adaptation process, I undertook research to complete the LCLIP myself. Through this study, I was able to explore the LCLIP method, research its utility and application and gain first-hand experience of undertaking an LCLIP as part of the wider adaptation strategy. In addition, leading on this work also allowed me access to closed door discussions within GCC, providing valuable context and insights. The aim of the LCLIP’s was to identify how an organisation has in the past been affected by climate impacts, if there any impacts that may pose an emerging threat and identifies any measures currently in place to address such impacts (UKCIP, 2009). To complete the LCLIP, a database of extreme weather events and their related impacts is built via a media trawl and review of departmental records, which can be supplemented via interviews. To build the evidence base for GCC on climate impacts, I completed an LCLIP by reviewing 163 media articles on climate impacts experienced during the period 2007 to 2017 and completing semi-structured interviews. The semi-structured interviews collected information on how organisations had been affected by climate impacts, how they recorded data relating to such events and how this did (or did not) inform adaptation decision-making.

on climate impacts were unable to provide such data. Semi-structured interviews with GCC departments and arm's length organisations (ALEOs)[33] along with local education institutes, utility providers and community groups[34] revealed that only 30% (5 of the 17 entities) interviewed had a formal weather event recording procedure in place. The departments or organisations who did record impacts or have monitoring procedures and incident reporting systems in place, however, did not typically capture small events or detail on causes[35]. The limited information means it is hard to extract what the climate impacts experienced are to date and consider future impacts.

It was highlighted that there was a need for locally relevant data, particularly on vulnerability. Interviewee #12 commented that there was need for greater information on people at risk and vulnerable groups at a granular level. Also a recognition that whilst flooding was well understood, heat wave risks and associated thresholds were not known or captured. Similarly, interviewee #18 states, "we need expertise of how specific buildings and locations are going to be impacted – there is currently a lack of detail at this level".

The extent to which climate impacts were recorded was influenced by context. For instance, interview #13 highlighted that "The amount of detail recorded for events depends on location of event as well as timing in the political cycle. We know the response will be influenced by public and political interest". The interviewee also highlighted quantitative figures and evidence of impact may not be visible at the time of the incident, due to delays of knock-on effects and lags in becoming aware of any changes. It was stressed that extreme weather events may be times of stress and chaos, as interviewee #13 noted that during events "forms are not a priority" and are still seen as aspirational.

---

[33] GCC has established a network of wholly and partly owned Arms' Length External Organisations ("ALEOs") which provide services to and on behalf of GCC.
[34] This approach is different than suggested LCLIP method, as it goes beyond just GCC. The reason for extending these interviews beyond just GCC was because GCC was creating a city-wide not just council-wide adaptation strategy and action plan through the participation of this wider set of stakeholders. Therefore, it was relevant to understand how they had experienced climate impacts, how they were planning for climate change, the process to identify and appraise adaptation actions and how these activities relate to the development of Glasgow's climate adaptation strategy and action plan.
[35] Their procedures do not record the cause but only the impact of an event. As such, they maintained a record of number of plumber call outs but did not record whether the flooding or water problem was due to pluvial or fluvial flooding or merely a burst pipe.

The results of questionnaire #1 illustrated stakeholder perception of different types of climate impact data. The results of the questionnaire, illustrated in Figure 6.5, highlighted that the economic costs were seen as most helpful in which 90% of respondents indicated that economic costs are ‘very helpful’. Analysis of media reports and non-economic quantitative information (such as number of calls to emergency services) were seen as being somewhat helpful to 60% of respondents and very helpful to 40% of respondents. Questionnaire responses indicated that anecdotal comments on experiences of weather events, however, were seen as less useful or not helpful at all. It was found, however, during the semi-structured interviews that a focus on previous weather events made it more tangible as interviewees were often noticeably more comfortable talking about their experiences of past weather events and adaptation to such events, than when asked about future scenarios of climate change. This finding agrees with Brownlee et al. (2013) who suggest that climate impacts help bridge “the gap between the abstract and concrete”, thus making it easier to have discussions on climate-related change as they appear more tangible.

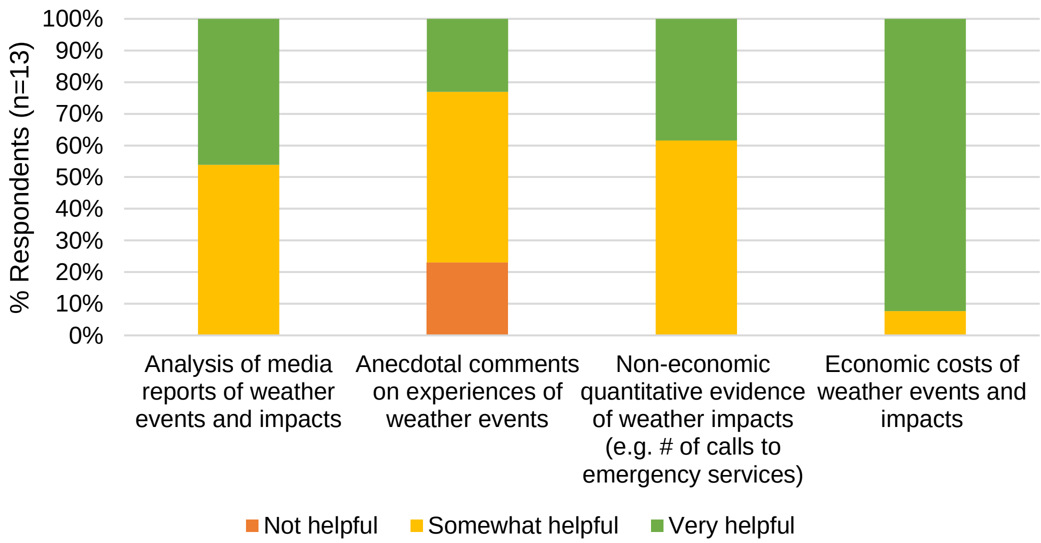



*Figure 6.5: Graph of survey responses relating to perceived helpfulness of types of weather event impact information (n=13).*

The results of the LCLIP (summary available in Appendix VII) subsequently led to a climate change risk assessment for GCC being undertaken, as the process highlighted Glasgow (and the council) were already experiencing adverse effects as a result of weather and climate events[36]. The risk assessment was intended to further explore risks to inform decision-making and strategy development. The risk assessment was produced in 2017 but not promoted internally or published externally. For instance, the outputs of the risk assessment were not shared with stakeholders involved in the adaptation workshops identifying and appraising adaptation actions. This stemmed from the lack of confidence by the adaptation lead in the assessment, interviewee #14 stated "I didn't share risk assessment as I wasn't sure how accurate it was". This appeared a missed opportunity to share data and generate further insight and evidence within the strategy and action plan development.

Information sharing was another influence identified. Interview #23 commented that there needs better connecting of existing data and sharing of information as well as improved links to academia. Questionnaire #2 responses found data gathering and sharing as an identified barrier to adaptation in Glasgow. Interview #14 also highlighted the role of Adaptation Scotland and Climate Ready Clyde in supplying data. This emphasises the role of boundary organisations in supporting and building capacity of local authorities.

In terms of weather forecasts and information, interviewees stated that sufficient information and data were available for immediate preparatory action to upcoming weather events. Interviews #3, #11 and #12 highlighted the excellent communication between emergency management (including Police Scotland and GCC Resilient Emergency Services contacts) and the Met Office. When asked about additional information or data needed, responses typically related to a desire for more localised and granular data. For instance, interviewee # 13 cited the need for SEPA rainfall data at a more localized level because it was felt that weather and subsequent consequences was wide ranging between different parts of the city. The need for economic data was also cited. Interviewee #9 stated, "in the current political environment, officers need information about the economic costs of weather impacts to the council's services to be able to build the business case for adaptation, gain the

[36] The adaptation lead felt that the LCLIP identified key areas which had been affected by previous weather-related events and therefore mandated a climate change risk assessment to be completed. The risk assessment was undertaken by the adaptation lead via a desktop exercise to create an initial risk assessment.

leverage to secure resources and institutional license to implement actions". Interviewee #15 even said, "I don't think there's anything we would not benefit from [in terms of data] as can not  have information overload on this topic".

To sum up, content or lack thereof, was observed to have a significant influence on the adaptation decision make process. Findings from this research demonstrated that data and evidence collection on climate impacts was neither robust nor consistent. The following section explores how this content was used to inform decision-making processes.

### 6.4.3 Process: decision-making process of options identification, evaluation and prioritisation

The third aspect of the CCP framework is process. Process within this study, refers to the steps undertaken for decision-making, including options identification and evaluation and prioritisation. Both the Resilience Strategy and the Adaptation Strategy and Action Plan used prescribed tools and resources to inform decision-making, namely 100RC and Adaptation Scotland resources. The following section details the activities completed by GCC to aid options identification, evaluation, and prioritisation for both strategies.

#### *6.4.3.1* Options identification

For the Glasgow Resilience Strategy, a wide range of engagement events were undertaken to identify appropriate options for consideration. On-street consultations and surveys were conducted by GCC across the city, including in areas where there were low levels of civic engagement[37], asking what citizens felt was needed for the city to become more resilient. Options identification also occurred through: (i) recording actions already undertaken in practice in the city; (ii) an actions proposal

[37] GCC publicly consulted via face-to-face conversations at 15 locations over 25 days receiving 1,500 responses. A "living room set up" with couches and coffee tables was brought to locations to create a safe space for open conversation with citizens about what they felt was required to make Glasgow "resilient".  Children were also engaged through 'My Glasgow Hero', an activity where children drew a superhero who could help Glasgow.

form circulated to stakeholders; and (iii) a review of emerging activities and good practices from other 100RC cities.

The Adaptation Strategy and Action Plan development was premised on a climate change risk assessment informing adaptation options. The LCLIP and CCRA were undertaken to serve as the evidence base for action identification. Interviewee #14 indicated that they felt the high-level risk assessment would identify priorities for action and justify low regret and no regret actions[38]. GCC believed that by developing the understanding of climate risk, this would inherently identify appropriate actions to mitigate the identified risks. Direct linkages between risks and proposed actions did not, however, occur, as a result of stakeholder input, bias, and limited resources.

Options for the adaptation action plan were sought via stakeholder engagement. Workshops were organised seeking proposed actions from organisation, businesses, and communities across Glasgow. GCC requested that actions proposed be either actions already under way, those that are confirmed and will start shortly or those planned for the future but have not yet been fully confirmed. The option for new actions to be proposed was only available if they were proposed by organisations in the partnership and could be undertaken by the organisations directly (this was because of limited resource availability for new council led actions). Actions were requested relating to the themes of: (i) evidence to inform decision-making; (ii) building capacity to adapt; and (iii) taking action on the ground.

The questionnaire distributed at the three Climate Resilient Glasgow workshops (Questionnaire #2) asked respondents if they had proposed an adaptation action and if so, how was this done. The majority of the responses to this question (as not all did propose actions) indicated this was done through conversations with colleagues about what was ongoing or needed and did not involve consultation with data or evidence. It was commented that this was a rushed process, due to time pressures. Workshop invitations prompted stakeholders to identify potential actions quickly in advance of the event, as opposed to taking time to canvas all possible options.

[38] According to Füssel (2007, p.273) low regret and no regret actions are “actions whose costs in a broad sense are small or even negative under all plausible climate scenarios)”.

Observational research at the adaptation options appraisal workshops in August 2017 (as a facilitator), identified that most adaptation actions proposed did not respond directly to identified impacts. Instead, most adaptation actions related to themes or areas that stakeholders were already engaged with or what was on their work horizon. Therefore, an identified challenge pertained to the level of detail, or lack thereof, of the proposed adaptation actions as well as lack of critical reflection on the actions proposed. Most adaptation actions proposed were vague and ill-defined, whereby they had unclear goals which makes it challenging to assess the best decision. It was commented by attendees at workshops that the benefits of the adaptation options could not be derived. Examples include general capacity building and education of citizens without specification on the who, what, where or how.

There appeared a preference for awareness raising and capacity building activities rather than actions to address tangible risks. During participant observation at a taskforce meeting, the following comment by a group member was made: “Sometimes people just don’t know what they need to do – we need to identify best practice to guide them”. This reiterates the common belief from stakeholders engaged in this research that it was felt more capacity building was needed to support adaptation action. Interviewee #14 also reflected that “maybe there was a lack of understanding of what the problem is and maybe it wasn’t clear what we [GCC] wanted”.

#### *6.4.3.2* Options appraisal

Options appraisal refers to an evaluation and comparison of identified options (Werners, 2013). Both processes studied were designed and implemented in an ad-hoc manner. The experience of option appraisal is presented here.

To appraise the options identified via engagement for the Resilience Strategy, a ‘Resilience Lens’ workshop was held in early January 2016. At this meeting, attendees (working group leads, the platform partner,[39] ARUP, and representatives of GCC)

---

[39] 100RC identified consultancies and businesses that were available to provide support to participating cities. Arup was the partner chosen to work with GCC.

selected actions to be incorporated into the Resilience Strategy. There was an intended process for the workshop, outlined in strategy development guidance provided by 100RC; to score and rank each proposed opportunity within their respective sectors (People, Place, Institutions, Economy) and then assess their co-benefits across sectors. The scoring process, however, was not undertaken due to lack of buy-in with the process and limited time available for assessment. One participant noted that potentially there was not enough data to assess sufficiently or to complete the Resilience Lens spreadsheet provided by 100RC. Instead, an ad-hoc, non-prescriptive process was done, whereby stakeholders shouted out their perceived favourites and these were discussed. A rush to appraise options was observed, as there was a desire from council staff to speed up time spent to meet the deadlines of external 100RC funders. Interviewee #3 reflected on the 100RC process saying they found it “laborious, long winded, lacking structure…the goal posts were getting moved constantly – every time we thought we’d got somewhere the goals moved – often by 100RC or ARUP – almost every time I went to a meeting they came with a different template.”

Options evaluation for the climate adaptation strategy and action plan were intended to be led by stakeholder dialogue. At the workshops, the proposed options were discussed in small groups with comments recorded on flipcharts. The number of actions proposed, however, were so numerous that not all were discussed in detail. Interviewee #14 commented “there were too many to look at meaningfully”. A criticism that was raised by a task force member was the siloed nature in which options were identified and assessed, which were undertaken within the SCCAP1 themes of Built Environment, Natural Environment and Society & Economy. A workshop attendee commented that by not looking at them holistically, GCC were restricting options identification and appropriate assessment. It was also queried by attendees why there were no set criteria to assess the actions against other than if they were able to be conducted in partnership.

The process used to evaluate the proposed actions was also not well received by engaged stakeholders. Questionnaire #2 asked for feedback on how participants found the workshops. Responses included: “Key stakeholders were not present” and

"Concern that the process may not be objective". These comments highlight some of the limitations of the decision-making process used, including not having sufficient resource, engaging appropriate stakeholders and subjectivity involved in the process to identify and appraise adaptation options.

A lack of assessment criteria also limited evaluation of proposed adaptation options. An interview with the adaptation lead (interviewee #14) after the August 2017 workshops revealed that following the feedback received from stakeholders, GCC's process of appraisal consisted of reviewing the action owner and relevant timescales for implementation but little else regarding the proposed action. The desire for departments and organisations to self-identify and importantly act as action owners (and funders) was so strong, that there was no further review process to assess actions. A significant restriction, highlighted by the adaptation lead, was the lack of action owners associated with the proposed actions, meaning that there was no appetite to lead or take them forward. There was also no connection between the evidence base generated through the CCRA and LCLIP to ensure the identified risks would be appropriately mitigated with the proposed adaptation actions, or not.

In addition, during interviews stakeholders were asked how adaptation decisions were made in their departments or organisations specifically. Most organisations 'hadn't got to that point yet'. Interviewee #13 revealed that "we prioritise based on CBA, but we struggle with putting weighting on co-benefits of business case. We use SG [Scottish Government] guidance on CBA and CIRIA SUDS tool, we look at cost of damage versus cost of intervention and calculate net present value but even a positive CBA doesn't mean it will get approved or funded, depends on resource and senior managers." It was felt that co-benefits were not well understood or appreciated within the decision-making process.

In summary, the options identification and appraisal processes used, for both the Resilience Strategy and Climate Adaptation Strategy and Action Plan, were poorly defined, detached from the data and evidence or content collated, subjective, and did not use decision support methods. Participant observation indicated these choices were a result of time pressures, lack of familiarity with decision support methods available, limited confidence in applying them and perceived impracticality of such methods. Whilst evaluation and prioritisation of actions is arguably an important step in strategy development and action planning, it does not appear to have been given much recognition or consideration in the strategies studied. For example, in the Resilience Strategy, options identification was strong due to widespread engagement, but appraisal and prioritisation was poor due to decision makers not adhering to agreed process, attempting to speed up discussions and adhere to pre-established organisational priorities.

The Adaptation strategy options identification was weak. This was due to limited data and evidence availability, disregard for existing data to inform options with a preference for actions which already had committed funding. In addition, it appeared there was an underestimation of adequate time required for the adaptation process. This may result in challenges where the adaptation actions that are prioritised are not the most effective or most feasible (Action on Climate Today, 2016). It must also be highlighted that data collection for this research stopped in February 2020. It is recognised that more developments have been made by GCC since this time, particularly the re-establishment of Sustainable Glasgow working groups and COP26 preparation and related projects. However, for the purpose of writing up this thesis, a cut-off point had to be made. The previous sections, based on the findings of this research, have summarised the individual influences of context, content and process on decision-making as outlined in Table 6.4. The following section explores interlinkages between CCP and analyses findings in relation to relevant literature.

*Table 6.4: Summary of findings from GCC study with respect to content, context, and process*

| CCP Element | Definition in Study | Data Collection | Identified influences challenging decision-making |
|---|---|---|---|
| Context | The broader environment in which adaptation decisions and actions are made (including both internal and external context). | • Participant Observation<br>• Contributions from interviews<br>• Questionnaire #1 and 2<br>• Document analysis | 1. Lack of resource constraining options<br>2. Lack of awareness and buy-in for adaptation leading to lack of leadership<br>3. Increasing pressure from civil society to take action on climate, but focus on mitigation<br>4. Wider policy levers influencing senior buy-in and responses on adaptation. |
| Content | The data and evidence used to inform decisions. | • Undertaking the LCLIP<br>• Interviews<br>• Questionnaire #2 | 1. Poor recording mechanisms lead to lack of locally relevant data<br>2. Data and evidence not being collected or presented on topics that matter most – financial implications.<br>3. Stakeholder perceptions or preferences considered more than quantitative evidence. |
| Process | The steps involved to identify, evaluate and prioritise options. | • Participant observation<br>• Conversational interviews with adaptation lead | 1. Data and evidence not consulted to identify options – stakeholder feedback<br>2. No set evaluation criteria used to prioritise options<br>3. No decision support methods used leading to unstructured, ad-hoc process. |

### 6.4.4 Interlinkages between context, content, and process

This section discusses the interlinkages of context, content and process and their influence on the adaptation decision-making process. A strength of the CCP framework is offering the ability to explore and map interlinkages between CCP (Iles & Sutherland, 2001). The following section explores the relationships between the identified influences and potential underlying causes for the challenges. This is important as it is in these spaces, or intersections, where significant challenges to and opportunities for decision-making may reside.

#### *6.4.4.1* Process – context

Action research with GCC highlighted how contextual factors such as national policy, citizen pressure, internal organisational leadership (on adaptation), awareness of climate change and support for adaptation can all influence the decision-making process. Adaptation decision-making processes were negatively impacted by the sparse resource availability within the study. I observed a lack of robust options identification and appraisal processes which resulted from the limited resource, in terms of data, information, staff time and money. The rush to make decisions was driven by the lack of time allocated to adaptation. This section will discuss these influences between process and context in turn.

Firstly, it is recognised that the broader policy framework and governance processes at the national and regional level influence local institutional context. This can also influence resource availability due to potential lack of institutional autonomy (Measham et al., 2011). This was observed in this study, for example with repeated comments observed at Adaptation Taskforce meetings and workshops about how the Scottish Government were not providing adequate funding and finance accessible to councils for climate adaptation. Even the Scottish Government’s Climate Challenge Fund (CCF) for community led climate projects only funded low-carbon, mitigation activities as opposed to adaptation initiatives. Furthermore limited resource availability can lead to a preference of near term, responsive actions, rather than long term systemic solutions (Crabbé & Robin, 2006). Multi-level contextual issues thus affected process. The extent and structure of national adaptation policy was reflected in the approach to adaptation at the local level within GCC aligning options evaluation with SCCAP1 themes. National adaptation context however did not provide further addition resources to allocate staff and time within the local authority to address adaptation. Which led to adaptation ‘competing’ against other priorities in the council for funding, such as housing, economic development, transport, as opposed to enhancing the resilience and contributing to the outcomes of these sectors.

Published literature also has shown how decision-making processes are influenced by context. Organisations influence collective decision-making by restricting, enabling or incentivising actions, through distribution and allocation of power, shaping beliefs and social learning (Oberlack, 2017). In the context of mitigation, Rickards et al. (2014) found that civil servants are focused on their professional context and near-term pressures, which relate to reputation, relationships and financial status, which has synergies with adaption findings in this research. Findings demonstrated that decision-making processes were influenced by the context in which they were occurring.

The options prioritisation process was also influenced by broader contextual factors. For instance, at the workshop, multiple participants stressed that it was important for the resilience strategy to align with existing city council objectives for it to be well-received and accordingly, resourced[40]. For example, in this study GCC were observed to select options (for both resilience and adaptation strategies) that aligned with current GCC goals, which were not necessarily aligned with adaptation needs, demonstrating institutional lock-in. Participants also highlighted the need to consider upcoming city council elections and the future political make-up of GCC's leadership. As a result, it was suggested to use GCC's own strategic plan objectives as goals within resilience strategy and as criteria to assess the options in order against the objective of to "put resilience into the bloodstream of GCC". Observations highlighted that decision-makers felt they had to operate within pre-defined norms and that their duty was to make decisions to maintain the status quo of the council. This approach may show strategic thinking on potential of mainstreaming resilience across an organisation but also limitations if mainstreaming has to fit in the grain or the goals of the organisation which may not be that forward thinking or future proof, highlighting the overlap between context and process.

Path dependency, policy succession, inheritance, and dependence on locked-in aspects such as governance structures and decision-making mechanisms are all elements of context which can influence adaptation decisions. Organisations may be challenged by institutional inertia, path-dependence, and a preference for incremental over transformational change. Such path dependency is determined by historical precedent, context and resulting structures and institutions (David, 2007) which can

[40] The motivation behind aligning the strategy with city council aims was influenced by funding. 100RC did not provide financing for implementation (apart from providing use of platform partners if cites sign up to the 'Resilience Pledge'), only strategy development which meant that many of the opportunities identified were pre-existing or already planned actions, in order to be resourced.

result in lack of willingness to alter business as usual. Historical institutionalisms can lead to power asymmetries and path dependence (Patterson et al., 2019). Similarly, Barnett et al. (2015) in their studies across Australia on barriers and limits to adaptation, found that path-dependent institutions which are resistant to change, can limit adaptation, particularly where climate change outpaces the rate of organisational change. Within this research, it was observed a preference to stick with the status quo. For instance, selecting actions which were already ongoing and preferred by senior leaders. Findings indicated a constrained and narrow adaptation space (scope of adaptation) whereby adaptation options were only identified and deemed appropriate if they were already available to the organisation, as Berkhout et al. (2006) also found as a barrier. This may indicate a tendency for incremental as opposed to transformational change, potentially as a result of historical precedence and policy dependency.

Context can also influence process depending on how an organisation ‘frames’ adaptation (Moser & Ekstrom, 2010a). In observing GCC, adaptation was interpreted in a linear fashion, with climate impacts being identified, climate risks predicted, and then appropriate responses provided. This did not occur in practice, with decision-making being much less structured and more opportunistic. As Ballard et al. (2013) suggests, the mindset behind this approach may also fail to appreciate the capacity, knowledge and skills required for adaptation decision-making. Furthermore, there is also a requirement for energy and enthusiasm for the topic. For instance, interviewee #18 said, “I suppose you have to take the broader context into consideration – like capacity and resource and austerity. If you’re asking people to put extra effort in when they don’t have the resources to do so, you’re really relying on people’s goodwill.”

This research is studying adaptation focused decisions; however, it is recognised that climate considerations will need to be made in all decisions but context still affects these processes. This was highlighted in interview #21. The interviewee stated, “the requirement to consider climate change in decision-making processes is certainly not comprehensive and therefore people overlook it and don’t take the opportunity to build in adaptive capacity and resilience. A good example of this is the City Deal. There was a strong requirement to demonstrate added value in terms of employment as a consequence there has been a limited attention paid to adaptation rather than being seen as a strong co-benefit for delivering grey infrastructure projects - [this is a] missed opportunity due to lack of awareness…or if there is awareness then it's just not seen as a priority." In summary, the context influences of lack of resource and commitment led to a process which was ad-hoc and ultimately only enabled incremental, path-dependent change. The next section discusses the relationship between contextual factors and how content, or the data and evidence used to inform decision-making is addressed.

#### *6.4.4.2* Context – content

Context and content were also observed to exhibit strong linkages. These included (i) lack of leadership on adaptation and limited local data and information having a reinforcing negative relationship and (ii) lack of technical skills to be able to access and use information. This section will discuss each in turn.

A reinforcing relationship between the contextual void of leadership and lack of data collected and used was identified. It was stated by interviewee #14 that challenges relating to lack of knowledge or awareness limited ability or interest in collating evidence. Similarly interview #12 revealed the barrier to action was that adaptation is not seen as a priority because there was not enough information about climate change and potential impacts in Glasgow, making it hard for to departments to plan. More evidence was believed by the adaptation lead to support a stronger argument for real actions.

This oversimplification may not recognise the inherent political challenges of evidence based policy making that has been well documented in policy sciences (Cairney & Jones, 2016). For instance, interview #5 when asked about the use of local information to inform climate resilience planning replied "There's probably a little bit of reactiveness. You know, if there's a flood, then that might make them consider doing something in a particular area, even if it's not the area most in need. It's all very well being strategic, but I suppose local politics comes into play." There is a burgeoning body of literature on how and when climate information is used by decision makers (Johansson, 2015; Van Der Sluijs & Wardekker, 2015). Lemos et al. (2012) highlight that climate information is not used optimally or frequently by decision makers due to the data characteristics, decision context including institutional factors and individual characteristics of the decision maker (who themselves are unlikely to be data analysts) and may be driven or motivated by political or institutional agendas.

Cognitive processes and psychological characteristics, including attitudes, technical knowledge and ideological or political leaning, also influence how decision makers use climate information within their decisions (Orlove et al., 2020). Similar constraints recognised in literature include the role of limited information, in particular relating to climate impacts at a local level or the inability to access or use climate projections or scenarios (Crabbe & Robin, 2006; Dessai et al., 2005; Measham et al., 2011). The necessity to ensure such information is communicated appropriately to managers, planners and elected officials to best inform decision-making and influence action was also found by Amundsen et al. (2010).

This study contributes to the literature through its finding that despite an interest in generating climate information (via the LCLIP and CCRA), there was limited use of the data within the adaptation decision-making process, and this appeared to be due to constraints in time, limited resource and lack of organisational commitment and leadership on adaptation. Observations also identified that there was a divide between resources available and what GCC were able to use and implement themselves. The decision-maker (the lead on adaptation within the council) was not able to utilise the latest UK Climate Projections (UKCP18) user interface and thus relied on outdated UKCP09 data downloaded by a previous colleague. Thus I argue that training and capacity building are essential to enhance climate adaptation decision-making.

The lack of awareness and buy in for adaptation and its effect on investment in capacity building and resourcing adaptation has been identified in the literature and was witnessed in this study (see Section 6.4.1.2) (Berkhout et al., 2006). Wilby and Vaughan (2011) stress that the capacity of leaders to create and sustain momentum on climate change is important. Absence of leadership in this context undermined data collection and information exchange. The ability to access and interpret climate information was further exacerbated by skills and experience of staff. The need for staff with skills to identify and use data to make the business case for adaptation has been identified in the literature (Berkhout et al., 2006; Westerhoff et al., 2011). However as Power et al. (2018) note, generalist staff with limited technical training and high turnover within the organisation is often common in local authorities. This was witnessed within this study with considerable fluctuation of the Sustainable Glasgow team size and composition. In summary the organisational context, heavily influenced the content available and used within decision-making.

#### *6.4.4.3* Content – process

The content, or depth and availability of information relevant to adaptation decision-making was also observed to affect decision-making processes. Studies have shown that improved scientific and technical information, does not necessarily lead to improved decisions (Kirchhoff et al., 2015). It was observed in this research, that the data and evidence gathered did not directly inform options identification or evaluation. Therein lies a problem with academic conceptual framings, which focus on enhancing the supply of evidence to respond to bounded rationality framings of decision-making rather than focusing on the actual demand for evidence.

It was revealed that decision makers often are only be able to compile limited information before they have to make a decision (interview #14). This limitation on time to identify and appraise options, encourages the selection of a solution that already exists, and the use of shortcuts to gather information in a short time scale (del Campo, Pauser, Steiner, & Vetschera, 2016). This can result in decision makers not maximising, but satisficing. Satisficing relates to searching for ’good enough’ solutions as opposed to optimising which is searching for the ‘best possible’ solutions (Berkhout et al., 2006; Orlove et al., 2020). The relationship between content and process, as well as other overlaps between context is summarised in Figure 6.6.

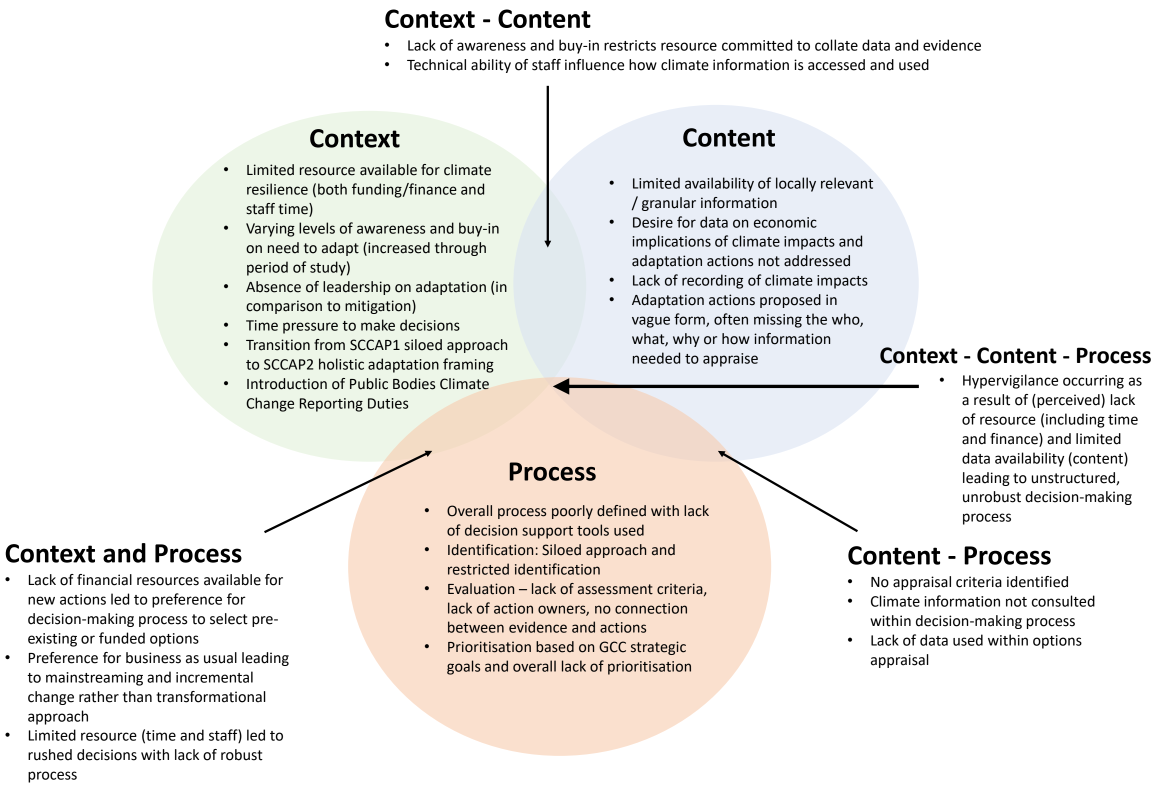



*Figure 6.6: CCP Interlinkages. The CCP is used as a lens to explore the relationship between the influences affecting context, content, and process. The image shows the relationship between each of the factors as well as the cumulative effective of influences being present.*

### *6.4.4.4* Context, content, and process together

Applying the CCP framework in the context of adaptation decision-making enables the exploration of context, content and process, individually, in pairs and also holistically (Iles & Sutherland, 2001; Pettigrew, 1990). This section considers the relationship between all three influences and how findings relate to those in previous published studies. The manner in which these challenges interacted and were responded to, provides useful learning for other cities.

This research affirms Eisenack et al. (2014) finding that different barriers cannot be understood fully in isolation given their interdependencies. For instance, in this study a lack of resource led to lack of information and coordination. Lack of organisational support led to lack of decision-making processes. Expanding on Eisenack et al. (2014), these research findings demonstrate that influences on adaptation are not static but highly dynamic. For example, the level of commitment to climate change increased substantially throughout study. It was unfortunately not matched with the same enthusiasm for resource commitment. Secondly, it was found that past decisions can hinder current or future adaptation, so it is important to look backwards as well as forwards.

This study acknowledges the need to explore the range of factors influencing adaptation decision-making and the relationship between them and understand them in practice through empirical research. A lack of leadership commitment to climate adaptation was demonstrated by the resilience strategy not having explicit adaptation references and adaptation work not being sufficiently resourced and repeatedly delayed. This analysis demonstrated the failure to identify and account for these interlinkages in this study, which led to an imperfect decision-making process. The need to explore the overlaps between context, content and process is supported by Westerhoff et al. (2011) who found that adaptation is supported via interacting factors aligning, such as political will, public support, sufficient resourcing and access to appropriate information.

As argued by Oberlack and Neumarker (2013), there are a large number of factors influencing adaptation which have been identified in the literature and there is heterogeneity of adaptation situations, meaning different settings will be caused by and influence different variables as well as their relative importance. Ekstrom & Moser (2014) identify four categories of barriers common to urban adaptation including institutional, attitudinal, financial, and political. Furthermore, Biesbroek et al. (2013) identify seven categories of barriers including conflicting timescales, substantive, strategic and institutional uncertainty, institutional crowdedness, institutional void, institutional fragmentation, lack of awareness and communication, motives and willingness to act and lack of resources. Lehmann et al. (2015) also found these categories which they renamed as information, resources, and incentives. However as Eisenack et al. (2014) highlight at this abstract level, many of these barriers don’t just relate to climate adaptation but could be attributed to a number of issues facing city councils.

Roggero et. al (2018) argue that further contributions which explore the institutional environment within which individual actors operate, would be beneficial. As Hinkel and Bisaro (2015, p.183) state, “there is lack of and need for more explanatory approaches to adaptation, particularly on behavioural and institutional aspects”.  Policy making is not always aimed at solving problems based on scientific data, but in many cases relates to political challenges that may relate to perceptions of evidence types, economic interests and aims (Tangney, 2019). Fussel (2007) highlights that decision makers and related budget holders must not only address unprecedented climate conditions but also the unprecedented rate of change which enhances the urgency to act.

The fact there are so many diverse barriers noted in the literature indicates that there is no single factor or influence that enables or restricts adaptation, and as such it is important to understand the context and dynamics in which adaptation is occurring. I recognise that the literature on adaptation challenges is a crowded space. The research findings presented so far in this thesis, largely confirm, and reinforce the findings on common barriers presented in the literature.  I do not claim that this list is exhaustive in its identification or mapping out of dependencies between barriers, but I argue it is a step towards the research needs identified by earlier studies. In addition, this research sought to explore influences on adaptation decision-making generally. As such, analysis didn’t differentiate between incremental and transformational adaptation. This study also did not explore actor specific characteristics extensively but instead explored institutional characteristics and conditions.

This study focused on deep dive in GCC, however in order to determine how generalisable the findings were semi-structured interviews were undertaken with adaptation practitioners working at boundary organisations in Northern Ireland and the Netherlands who had supported adaptation decision-making processes in numerous cities in their countries. This study sought to validate findings via interviews with other countries. The following section presents the resulting findings.

#### 6.4.5 Validation

Several discussion points were identified as a result of the findings presented so far. To understand how generalisable findings were, two semi-structured interviews with boundary organisations (intermediaries who provide adaptation advice, services and capacity building support) in the Netherlands and Northern Ireland to assess generalisability of findings were conducted. These two nations were selected for perceived differences. The Netherlands is regarded as advanced in terms of climate adaptation (given their necessary adaptation actions as a result of their geographical vulnerability to climate change and public commitments to the topic – the Global Centre for Adaptation is based in Rotterdam), whilst Northern Ireland would be a less mature nation on adaptation (as climate legislation is not yet enacted in the region). Interviews were undertaken with stakeholders in Northern Ireland and the Netherlands to explore if the findings from Glasgow (relating to CCP influences) were being observed elsewhere. Semi-structured interviews asked about the context (both externally and internally), the content (data and evidence used), and decision-making process used in both locations.  The results are summarised in Table 6.5.

These international interviews supported findings from the GCC study and published literature. The difference in data collection, however, was noted. A one-off interview did not gleam the level of detail or insight as observational study or multiple interviews over a long period of time. The process of validation led to the development of some additional observations which are presented in the following section.

*Table 6.5: Summary of interview responses exploring CCP influences with adaptation practitioners in Northern Ireland and the Netherlands*

| **Country** | **Northern Ireland** | **Netherlands** |
|---|---|---|
| **Organisation** | Climate Northern Ireland (n=1) | Climate Adaptation Services (CAS) (n=2) |
| **Context** | The contextual influences identified in this study were also experienced in Northern Ireland. The external context, however, was found to be more restrictive in Northern Ireland in comparison to Scotland given that there is no national policy. Two bills are currently being considered but at the moment local authorities are not required or mandated to undertake climate adaptation action at all, it is voluntary. This is in opposition to the context in Scotland, where action by public bodies is mandated via legislation (Climate Change Scotland Act, 2009). In addition, the size of local authorities in NI is much smaller and their role and responsibility differs to their counterparts in Scotland. Responsibility for housing, roads and infrastructure is all held by central rather than local government, impeding their ability to plan or advocate for adaptation at the local level in those sectors.<br><br>As a result of this lack of policy and national support, there has been limited funding available for adaptation. This is further exacerbated by Brexit. The adaptation progress in Northern Ireland to date, primarily in Derry was a result of an Interreg project funded by the EU, which is no longer available. It was reflected by the interviewee that in Belfast in particular there was a 'lot of goodwill' for climate adaptation however there was 'still a lot of work to do in terms of turning that goodwill into action'. Under resourcing was noted as a constraint on adaptation as there is no staff member solely focused on adaptation in any of the six local authorities in Northern Ireland.<br><br>External contextual influences have also catalysed action in Northern Ireland. For instance, Belfast also participated in the 100RC initiative which spurred consideration on climate resilience and was driven by the city council. It was not felt, however, by the interviewee that citizens understood or were advocating for adaptation, yet. Internal context of local authorities was said to be influenced by management and also the occurrence and experience of extreme weather events. | The interviewees commented that they felt there is strong national support for adaptation in the Netherlands. The external context is shaped by the Delta Progamme, a national programme and collaboration between the national government, provincial authorities, municipal authorities and water boards. The objective of the Delta Programme is to protect the Netherlands and its future generations from high water and ensure a sufficient supply of freshwater. The Delta Act constitutes the legal basis for the Delta Fund, which can be used to finance the projects of the Delta Programme. The interviewee reflected that whilst this programme supports adaptation, it has a narrow focus on spatial adaptation and flood risk management. This is in comparison to Scotland, where the national adaptation policy (SCCAP2) is very holistic and integrates adaptation considerations across all sectors.<br><br>The identified influences arising from the internal context of local authorities was very similar to what was found in GCC. For example, influences identified related to limited budget or financial resource and human resource, as there was not enough capacity available to do adaptation related work. The interviewee had a full-time job on climate adaptation in a municipal authority but believed this to be very rare for the Netherlands. The creation of the role was a result of adverse flooding in 2014 and 2015 that increased awareness on the need to adapt. As such it was commented that generally adaptation was often reactive as opposed to proactive. Typically, adaptation is integrated partly into a pre-existing role as an add on. CAS undertook research on adaptation in municipalities across the Netherlands and found diverse results indicating the diverse landscape within municipalities. Progress appeared dependent on if a dedicated climate officer was employed, if enough funding was available internally and if an extreme weather event 'focused' the organisation's mind on adaptation. |

| | | |
|---|---|---|
| | It was identified that climate impacts, such as extreme flooding, had instigated response and subsequent adaptation planning or action. | |
| **Content** | The interview revealed that Northern Ireland had similar challenges with content or data, for adaptation, as GCC experienced. It was identified that there was a lack of local and/or granular data. The interviewee commented that data and evidence that is taken for granted in the rest of the UK is simply not collected in Northern Ireland, such as information on flood risk. It was noted that the majority of information being generated and collated on adaptation is qualitative. It was felt, however, that there is not an understanding of 'the full picture of what data we do and don't have'. | Similar to the experience of GCC, it was commented that local data was challenging. Risk assessments (and stress tests) are typically undertaken at a regional scale or water board level. Therefore, data were lacking in terms of local scale data and the interviewee commented that interpreting the data was difficult. The spatial data were not regularly updated, and older data were used. The interviewee stated, "so I struggle there. I can do some research on climate adaptation, but if the base data is not right, it's very hard." |
| **Process** | Northern Ireland uses a process adapted from the Adaptation Wizard (UKCIP, 2007). The interviewee revealed that most local authorities are still at the early stages of the adaptation cycle. Only two (out of six) councils have progressed to develop an adaptation strategy (Derry and Belfast). In terms of adaptation decision-making, it was commented that a risk register is used as starting point for identifying and considering actions. The process, however, was described as 'ad-hoc' and unstructured. It was commented that often proposed actions were early-stage activities such as communication and/or consolidation of existing activities. Adaptation options were found to be influenced, and to some extent pre-determined by the local authority environment and by what funding is available. Interviewee stated, "for the most part, it's very much what we're currently delivering and those are the structures that we're in and that's what we're designed to do, so actions align with what's already happening." It was highlighted that adaptation options appraisal does not currently occur in a structured way and would be an increasing area of work as local authorities matured and progressed their adaptation work. The need for decision support methods was identified by the Climate NI representative. | Adaptation process in the Netherlands is guided by the Delta Programme which suggests seven ambitions, including dialogue, stress testing and adaptation decision-making; however, it is not a sequential approach. It was reflected that in practice, adaptation is more ad-hoc and implementation doesn't always start as a result of stress testing / risk assessment. The suggested approach is to stress test to identify hotspots and then take dedicated measures to address. However, in practice it can often relate to identifying opportunities to integrate adaptation into existing or already planned measures, as opposed to new bespoke adaptation actions. It was commented that is difficult to get stand along adaptation actions. Mainstreaming was preferred.<br><br>Options are prioritised based on urgent areas identified within the stress test, as well as opportunities emerging from other sectors. No decision support tool or method was used to appraise options, it was stated selection was based on a 'gut feeling'. It was commented that there is an Adaptation Support Tool available for Dutch municipalities to assess costs, benefits, and consequences of different options however it's not used commonly in practice as it was perceived not to be user friendly. It was also commented that whilst the interviewee was aware of a lot of tools out there for decision-making, they were unsure what worked in climate adaptation. These findings are aligned with the experience of GCC, where the decision-making was ad-hoc and options identification did not relate to the risk assessment results. |

## 6.5 Discussion: Examining the challenges of climate adaptation decision-making

Through utilising the CCP framework, this research identified the influences of context, content and process on adaptation decision-making as well as highlighting the linkages between these concepts. Findings lead to the identification of two challenges impeding climate adaptation decision-making in the context of GCC. Firstly, that the influences identified in Section 6.4 are incentivising decision makers to become hypervigilant (as opposed to vigilant). Secondly, an argument is made that common adaptation guidance and decision support methods do not sufficiently account for the range of CCP influences nor do enough to mitigate against hypervigilance. I argue that these barriers or challenges arise, in part, due to inappropriate adaptation guidance and decision-support leading to hypervigilant behaviour. Each point is explored further here.

### 6.5.1 Reflections on decision-making processes observed

The context, content and process framework identified several influences challenging adaptation decision-making. These include limitations relating to time, resource and information availability as well as perceived competence of staff. Such influences were observed to result in suboptimal decision-making processes in the study context.

The findings presented in Section 6.4 highlighted a number of challenges affecting decision-making processes for both the resilience and climate adaptation strategies. In terms of context influences, a lack of financial resource constrained the options available. The decision-maker was forced to identify and select options which already had funding associated with the activities, thus restricting the diversity and potential appropriateness of the options. Secondly, the context defined when the decisions must be made. As detailed in Section 6.1, both strategy and action plans received several setbacks and delays due to other competing priorities in the council. Both strategies however had to then be finished at certain points to seek approval from internal institutional committees and ultimately the council. This resulted in long periods of waiting and bursts of activity to respond to time sensitive committee deadlines and demands of leaders. Such temporal influences also affected the decision-making process. The decision-making processes were relatively quick (less than a day for consideration), and neither employed a decision support method. The process was defined by the lack of time to assess options, the lack of financial resource available to identify or propose options and the lack of resources (human, financial and technical) which restricted the use of decision support methods.

The observations from this research, bear some similarities to hypervigilance. 'Hypervigilance' is a state of decision-making, where a decision maker is stressed due to time and resource constraints and searches frantically for options that address the immediate problem and all options are not considered (Janis & Mann, 1977). Hypervigilance is typified by a disorganised and inefficient process (Johnston et al., 1997). In comparison, 'vigilance' is where a decision maker confirms and agrees objectives to be achieved, searches for possible options, collates relevant information, assesses options in unbiased manner and selects options. A comparison of hypervigilant and vigilant states is offered in Table 6.6. This occurrence of 'hypervigilance' in this study appeared to be due to lack of resource putting pressure and strains on the decision-making, short term political life cycles, competing priorities and external citizen pressure. This was also observed in the findings identified from the Northern Ireland interview.

*Table 6.6: Summary of differences between vigilant and hypervigilant decision-making. Adapted from Johnston et al. (1997) and based on Janis and Mann (1977)*

| Vigilant Decision-making | Hypervigilant Decision-making |
|---|---|
| A. Decision maker thoroughly scans all available information | A. Decision maker scans only that information needed to make an assessment |
| B. Decision maker devotes a consistent amount of attention to each data point | B. Decision maker rapidly attends to selected data points |
| C. Decision maker reviews all alternatives before making a decision | C. Decision maker reviews needed information only when required |

The concepts of and differentiation between hypervigilance and vigilance arose from the 'Conflict Model of Decision-making' proposed by Janis and Mann (1977). This model suggested that decisions which involve doing nothing, sticking to the status quo or do not involve risk are typically easy, straight forward and have little stress and are referred to as 'unconflicted change', whereas when decisions require taking risks or making significant changes, this is referred to as 'conflicted change'. It is in the latter setting, where hypervigilance may arise.

The presence or absence of three conditions influence which coping pattern (hypervigilance or vigilance) is adopted. These are: (i) awareness of serious risks relating to preferred options; (ii) hope of finding better alternatives; and (iii) feeling that there is sufficient time to research and undertake the decision-making process (Janis & Mann, 1977). The conflict model of decision-making (Janis & Mann, 1977) highlights antecedent conditions of conflict situations, the mediating processes used to inform decisions and the consequences that result and thus can help aid conflict resolution (McDevitt et al., 2007). Hypervigilance is a symptom of these occurrences, rather than being a barrier in its own right.

The effect of hypervigilance has been found to restrict the canvassing of options. Keinan et al. (1987) studied the effects of stress (a feature of hypervigilance) on scanning and consideration of decision alternatives and identified three ways in which canvassing of options can be impaired. Firstly, premature closure may occur which is when a decision is made before all potential options are considered. This may be due to stress reducing span of attention, resulting in use of less data to inform the decision. Secondly, an effect which can occur is non-systematic scanning or a disorganised consideration of options (Keinan et al., 1987). Thirdly, temporal narrowing may occur when there is insufficient time to consider each alternative. Limited or ineffective canvassing of options can be correlated with poor decision-making[41]. Information gathering in practice may be spontaneous or systematic, whereas information analysis may be internal (using one's own believes and ideas) or external (using the opinions and insight of others). A vigilant decision maker will adopt a systematic and external information collection and assessment process (Mann et al., 1997).

It is evident that the observations recorded in this research setting more closely resemble hypervigilance than vigilance. For example, the process used to identify

[41] There is a lack of evidence on the effect of canvassing on decision process versus decision outcome. For instance, one may have a thorough identification and review of decision alternatives and still potentially choose an option which has negative consequences.

resilience and adaptation options was ad-hoc, chaotic and sporadic. Both processes focused on identifying ongoing, pre-existing, or planned and funded actions and rebranding or tweaking them accordingly. It was evident that GCC decision-making processes suffered from limitations through incomplete information, limited search (of options, in other words taking the actions that were ongoing, had been proposed or already had leadership support rather than the full spectrum of potential actions) and uncertainty. These findings were supported by insight from the Northern Irish and Dutch experience too.

There are, however, several key differences between the findings from this research and those of Janis and Mann (1977) who proposed the concept of hypervigilance. Temporality is a key difference. Climate change, or ‘the climate emergency’, is time constrained in a different way to other common emergencies. Climate change is often framed as a ‘slow emergency’, with a disconnect between the sense of urgency required to address (Howarth et al., 2021). Adaptation involves pro-active anticipatory and planned processes to prepare for climate change as well as reactive responses to climate impacts (Klein, 2003), as discussed in Section 2.4.2. For example, adapting to increasing risk of sea level rise necessitates both long term planning for gradual changes and emergency response plans for potential coastal flooding, which have different temporal interpretations.

Secondly, the time associated with making and approving decisions within a city council structure is different to the time allocated to emergency response when such an emergency occurs. The speed of policy making, and decision-making can affect how much information can be processed and/ or waited on (del Campo et al., 2016). The main limitation identified was a lack of time and resource to consider the problem thoroughly and explore options appropriately. Within this research, options were not identified thoroughly but instead opportunistically. In addition, repeatability is a difference for this research context. Emergency management has standard plans for events, whereas unprecedented climate change challenges our ability to respond given the new and unforeseen events and impacts.

Both of these differences (timeframe and repeatability), relate to a third difference, which is the type of problem being addressed. Decision problems can be categorised into different types. Grint, (2010) and Yawson, (2015) categorised problems into critical, tame and wicked. Critical problems are where the problem is apparent, but the solution is not. Tame problems are where the problem can be defined cand can be solved with technical know-how and skills. For critical problems, responders often act without seeking advice as they must do something immediately to respond. For a tame problem, decision makers can use tested and proven solution and expect a predictable response (Yawson, 2015). Wicked problems, however, are where there are no obvious definitions of the problem or the solution (Grint, 2010). For a wicked problem, decision makers must observe, interpret, and intervene.

Hypervigilance was proposed a challenge to decision-making for emergencies or critical problems, but not specifically decision-making for wicked problems. Wicked problems are unique in that they have a number of distinguishing characteristics including: causes of problem can be interpreted in multiple ways, there is no true or false solution, policy interventions are based on judgement rather than truth, there is no immediate test of a solution, every attempt is important and has consequences, every wicked problem can be a symptom of another problem and decision makers should try not to be wrong given the potential consequences of their actions (Rittel & Webber, 1973). Climate adaptation decision-making has been referred to as 'super wicked' because of its severe uncertainty, differing opinion and knowledge of stakeholders, dynamic interactions and limited understanding of responses and consequences (Head, 2014).

Hypervigilance comes from emergency management originally and therefore was borne in relation to critical problems. It is argued that a version of hypervigilance within GCC is occurring for the identification of climate adaptation options. As such it is proposed that a new interpretation of hypervigilance within wicked problems is needed. It is suggested this is referred to as RAFT decision-making. With this term being the acronym for resource constrained, ad-hoc, fast and time-constrained. The term RAFT is used to represent the characteristics witnessed as well as serve as a metaphor. RAFT decision-making is similar to the use of a life raft in that it is reactive, a short-term solution, not robust and indicative of a broader failure of systems or processes. The decision-maker clings to a raft which is being swayed by politics and resource availability.  RAFT decision-making is proposed as a term to describe the characteristics observed and processes witnessed as part of this research. Further research is required to assess if this concept correlates with other wicked problems, outwith climate adaptation.

To improve adaptation decision-making, I argue that RAFT decision-making characteristics need to be overcome It's impossible to fully eradicate influences challenging decision-making and so methods rather need to account for such influences and to mitigate risks. A question is raised as to how to best support climate adaptation decision-making if CCP influences lead to RAFT decision-making. This needs to be informed by appropriate decision support methods, which will be influenced by the stage of the adaptation journey. The following section (6.5.2) explores how the current adaptation guidance and decision support tools enable or mitigate against such decision-making practices.

#### 6.5.2 Shortcomings of adaptation guidance and decision support methods

This research suggests there is a disconnect between adaptation theory (Brown et al. 2011; Klein, 2003; Pelling & Manuel-Navarrete, 2011) and practice. Many of the challenges identified and encapsulated within hypervigilance (lack of time, pressure, and stress) are not well addressed in prevailing adaptation guidance and decision support methods. I argue, that in many instances, hypervigilance may be exacerbated as a result of inaccurate conceptualisation of adaptation decision-making by imposing unrealistic expectations.  This section thus discusses the shortcomings of common framings and decision support for climate adaptation.

Climate change adaptation is often interpreted as an iterative, cyclical, risk-based process (Willows & Connell, 2003). As discussed in Section 3.1, resources based on this idealised cycle are used in practice across the UK and Europe via the Adaptation Wizard (UKCIP, 2013), PROVIA Framework, RESIN's Adaptation Cycle (Chapman, 2018) and the UN-Habitat's Planning for Climate Change Guide (2014). The adaptation cycle mirrors the general policy cycle used across disciplines and sectors and espouses a rational and linear approach to decision-making (Styczynski et al., 2014). The rational approach to decision-making[42] implicit in these adaptation cycle resources, specifically details how a decision should be made to obtain the desired outcome. Limitations may arise since the classic, rational model of decision-making is underpinned by several assumptions embedded within the approach, many of which may not be appropriate for climate adaptation, particularly at the city scale. These include that the classic rational model assumes:

i. **The problem is clearly defined and well understood**

Rational decision-making assumes that there is a clearly defined problem with set goals and expectations of the decision maker (Lancaster & Lancaster, 1982). Climate change, however, is a 'wicked problem' (Pollitt, 2015) which means it may not easily be bounded and there may be unknown factors (Rittel & Webber, 1973). Milne (2015) suggests that forcing a problem diagnosis in situations which are unclear can result in oversimplification and/or misdiagnosis of the problem. There did not appear to be an attempt at understanding the problem within GCC, as observations revealed a more haphazard approach informed by funding opportunities as opposed to local climate adaptation needs.

Furthermore, the rational approach can often assume a project can be organised into distinct phases, such as understand the problem, gather information, analyse information, make decision, and implement. For wicked problems however Rittel and Webber (1973, p.138) argue that this demarcation is not possible stating, "One cannot understand the problem without knowing about its context; one cannot meaningfully search for information without the orientation of a solution concept; one cannot first understand, then solve." This study showed how studying the context, content, and process, one can identify systemic influences. The idealised adaptation cycle does not fully take account of the influences and interlinkages of context, content and process on adaptation options identification and evaluation, leaving the decision-maker at a loss for how to cope with such influences. I argue that decision-support should better help with system understanding holistically.

ii. **Information is available**

Rational decision-making also assumes suitable availability of knowledge about the problem and potential solutions, which, in the case of climate adaptation, is often unlikely to exist or be easily obtainable within the resources of a local

[42] The classical model for decision-making follows a systematic step-by-step process of: (i) listing all alternatives; (ii) ranking listed alternatives based on information; and (iii) selecting the most appropriate option. This approach is underpinned by economic theory which suggests that making decisions to maximise benefits and minimise costs (Tsoukiàs, 2008).

authority or city council. This was evidenced in section 6.4.2 which highlighted limitations in recording and accessing relevant local data. There is also an assumption that there is sufficient information available so that the decision maker can identify all alternatives and evaluate them objectively using measurable criteria within a suitable timescale. Yet, identifying and accessing measurable criteria for assessment within climate adaptation may not be possible, given data limitations, or may be challenged by tensions and conflicts amongst decision makers, as found in this study when no evaluation criteria were used. In addition, the rational approach assumes that decision makers are able to access and interpret data. I advocate for decision support which can use expert elicitation to address gaps in currently available information and builds capacity amongst decision-makers to interpret data.

**iii. Sufficient knowledge and competence of decision maker**

There is also an underlying assumption within the rational approach that evidence can be processed and understood by decision makers. The classical decision-making model assumes that individuals have clear and orderly ways to collect, process and interpret information about alternative ways to achieve objectives. It is also assumed that individuals can make correct inferences to make the most efficient decision. Etzioni (1992), however argues that the majority of decisions involve little or no information processes and typically use normative commitments, in other words doing what they feel they should do, or the organisation expects of them. Eiser et al. (2012) suggests that decision-making under uncertainty is no longer adequately served or represented by traditional rational choice frameworks, and there needs to be acknowledgement of the role of beliefs, values, and societal dynamics. Noted shortcomings have included lack of acknowledgement of individuals' cognitive limitations and no recognition of emotion or stress on decision-making process (Jones, 1999; Keinan et al., 1987).

This research found that unlike common conceptual adaptation decision-making frameworks, in practice the adaptation process observed in GCC was: (i) not linear or cyclical; (ii) not rational; and (iii) extended beyond risk framings. For instance, during an interview (May 2019) the adaptation lead reflected on the process of using the cyclical risk-based adaptation approach via the '5 Steps to Managing your Climate Risks' guidebook, stating that it "seems easy on paper but in practice it's not always linear, you don't always move forward, and external factors slows things down". For example, GCC adaptation efforts were set back several times due to competing priorities (adaptation vs climate emergency working group), limited resource (staff time) and as a result of the process (minimal attendance at workshops and lack of structured appraisal process. This was confirmed by the experience of Netherlands and Northern Ireland interviews which revealed significant delays to adaptation progress as a result of lack of collective buy in for adaptation.

In addition, the decision-making framework may not support wicked problems. As discussed in Section 3.2, wicked problems are: (i) difficult to identify, scope and define as there are multiple interpretations of the problem; (ii) have multi-interdependencies and can be multi-causal with conflicting goals; (iii) actions on wicked problems may lead to unforeseen consequences due to complexity of system; and (iv) wicked problems have no definitive solution (Crowley & Head, 2017; Rittel & Webber, 1973). This means that wicked problems such as adaptation necessitate holistic not linear thinking, flexible approaches which support learning, engage stakeholders to understand the problem and tolerate uncertainty (Lonsdale, 2012).

Thus, I argue, current conceptualisation of adaptation decision-making as rational is fostering or exacerbating a state of hypervigilance. Limitations on time to identify and appraise options, that often exist in practice, can predicate the selection of a solution that already exists, and the use of shortcuts to gather information in a short time scale (del Campo et al., 2016). This can result in decision makers not maximising, but satisficing, or searching for 'good enough' solutions as opposed to optimising which is searching for the 'best possible' solutions (Berkhout et al., 2006; Orlove et al., 2020). This was evident through the observation of the tendency to prefer simple actions which aligned with GCC goals rather than adaptation requirements. Similarly, timescales for GCC decision-making were constantly changing, reducing the time allocated and putting pressure on the adaptation lead to move to the next step in the cycle. Therefore, the representation of the adaptation process as a linear cycle may not be fit for purpose when applied in the real world which has a complex landscape of a context, typically defined by lack of resource and changing policy requirements.

As a result of the findings, I question if existing decision-making methods sufficiently recognise the influencing factors of content, context, and process to prevent hypervigilance. In order to transition to a more vigilant decision-making state, recognising that not all hypervigilant influences can be eradicated, methods must be able to change the perception of decision-makers and improve understanding of climate adaptation, explore the wide range of potential options and evaluate their possible consequences. A need to consider how decision support methods may increase vigilance is necessary and explored further in Chapter 10.

## 6.6 Conclusion

City councils are increasingly having to make complex decisions on climate adaptation (Webb & Beh, 2013). Developing robust empirical insight of adaptation in action is needed to support adaptation theory and practice (Klein et al., 2017).This research responded to this knowledge gap surrounding how organisational influences (arising from the context, content and processes used) challenge climate adaptation decision-making in practice, and thus affect which decision support methods may be most appropriate. This chapter discussed the development and decision-making process of GCC's Resilience Strategy and Climate Adaptation Strategy. Action research within the local authority over a period from 2015-2020 highlighted the complex and emergent nature of how Glasgow was building resilience and adapting to climate change.

Whilst elements influencing adaptation decision-making have been considered in the literature (Van Ierland et al., 2013; Wilby & Vaughan, 2011), there is limited empirical evidence of assessment of influences within organisations longitudinally. This research addresses this knowledge gap through a study of the dynamic interplay between context, content and process factors influencing decision-making for adaptation in GCC over the study period. These findings were compared to the experience of adaptation decision-makers in the Netherlands and Northern Ireland.

The results gathered through action research, demonstrate that organisational adaptation decision-making is strongly related to the internal awareness and buy-in for climate adaptation, enabling policy environment, competency of the decision maker (the context), the data and evidence consulted (the content) and the appraisal steps and mechanisms used to identify and evaluate adaptation options (the process). Challenges relating to the content used within options evaluations include the lack of relevant information, vagueness of proposed options and uncertainties in decision-making process. Challenges with the actual decision-making process included limited mechanisms to identify options and lack of methods to appraise potential options. These limitations were heightened by lack of awareness, leadership and resource devoted by the organisation and wider context. In addition, this research provides additional insight into the interconnectedness between context, content and process such as the knock-on consequences between the factors.

The empirical analysis presented in this chapter revealed that the CCP framework is suitable to explore climate adaptation in a city council. The different influences all aligned with the categories. Therefore, I argue that this framework could be applied to other cities to aid study and comparison between cities. It is a useful starting point discussion as it helps identify influences and then their relationships with other factors and potential dependencies or root causes. It is recognised that the context of adaptation is ever changing and not static. There remain several open research questions relating to influences on decision-making, namely the role of human behaviour and psychology and potential biases (which was not considered in great depth here). In addition as  (Lehmann et al., 2015) stress there is need to move towards more quantitative approaches rather than anecdotal evidence of challenges or barriers.

This chapter also argues that hypervigilant decision-making is occurring in practice for city level climate adaptation decision-making. Hypervigilant decision-making is typified by lack of thorough options identification, limited evaluation of options and insufficient time and resource for review. This thesis argues that rational choice models for adaptation, promoted in the likes of the Adaptation Wizard, are overoptimistic that data are available, the problem is well defined and there is sufficient knowledge as well as being insensitive to potential resource limitations (in terms of time, financial, staff, technical skills) possessed by individuals and organisations. There is thus a need for conceptual framings and decision support tools which overcome barriers causing hypervigilance and instead foster vigilant decision-making for adaptation and resilience where feasible.

A proposition emerges from this study which warrants further investigation and analysis. This includes that support is needed to aid processes of decision-making to identify, appraise and prioritise options for climate resilience. There is need for decision support that enables more thorough canvasing and options evaluation that can operate within the context and content limitations identified. Biesbroek et al. (2013, p.1119) note that "Although interventions to overcome barriers are recommended by most studies, empirical studies on interventions are scarce". A tenet of action research is the 'action' to propose and test interventions. To investigate these proposals further, the following chapter explores the process by which the researcher applied Bayesian Belief Networks and Qualitative Probabilistic Networks to appraise actions for the city adaptation action plan to assess their value in addressing influences and fostering vigilant decision-making practices. Chapter 7 introduces these methods and the methodology used. Chapter 8 then explores how such barriers may be overcome through experimenting with the application of a Bayesian Belief Network. This responds to the research need stated by Biesbroek et al. (2013) and Lehmann et al. (2015) who highlight the need to move from assessing barriers to assessing solutions, whilst acknowledging the former is necessary for the latter.

# Chapter 7: Methodology for Research Objective Two

Objective Two of this thesis was to assess the value of Bayesian Belief Networks (BBNs) and adjusted Qualitative Probabilistic Networks (QPNs) as decision-making methods to support climate adaptation decision-making within a city council and address challenges identified via Objective One. Two studies were undertaken to construct and assess a BBN and QPN separately. Research explored the development and use of BBNs and QPNs within the context of climate adaptation decision-making, by studying their application to support options appraisal to address pluvial flooding and heatwaves respectively. An introduction to BBNs in presented in Section 7.1 and a description of BBN elements is offered in Section 7.2, followed by the methodology used to construct a BBN within this thesis in Section 7.3. QPNs are then introduced in Section 7.4 and the QPN methodology presented in Section 7.5. Section 7.6 concludes the chapter by summarising how analysis was undertaken to address research Objective Two.

The decision to use the methods of BBNs and QPNs, resulted from (i) a high-level assessment of the applicability of common decision-making methods in relation to climate adaptation generally (as explored in Section 3.4) and (ii) the specific context, content, and process challenges of city-level adaptation decision-making in GCC (identified in Section 6.4). This led to the initial selection of trialling a BBN to support adaptation decision-making and a subsequent study on QPNs (based on findings from the BBN study, discussed in Section 8.4). Findings from the BBN and QPN studies are presented in Chapter 8 and 9 respectively and compared in Chapter 10.

## 7.1 Bayesian Belief Networks Overview

BBNs were introduced in Section 3.5. BBNs illustrate the relationship between variables and the likelihood of different outcomes occurring. BBNs use causal relationships and probabilistic calculations to depict a system where uncertainty is present (Vitabile et al., 2013). BBNs are able to do this and offer decision support through their use of Bayes' Theorem.

Bayes' Theorem, shown in Equation 1, is a one-line theorem that provides a method for calculating the validity of beliefs based on the best available evidence. It provides a set of mathematical rules for using new data to continuously update beliefs or existing knowledge. To explain further, Bayes' theorem provides a method whereby there is a hypothesis, H, for which there is a belief P(H) which is referred to as the prior belief about H. Using evidence, E, about H, the hypothesis, one is able to revise beliefs about H to then calculate P (H│E) which is referred to as the posterior belief about H (Fenton & Neil, 2019). The inferential process within a BBN operates by weighing one distribution, 'the prior', with another, 'the likelihood', to produce a third value, 'the posterior' (Heino et al., 2018).

$$P\ (H|E) = \frac{P(E|H) \times P\ (H)}{P\ (E)}$$

Equation 1: Bayes' Theorem

Bayes Theorem was originally developed in the 1700s by Thomas Bayes, a presbyterian minister and part time philosopher, statistician, and mathematician. For most of the nearly three centuries since the Reverend Thomas Bayes first made his contribution to probability theory, his ideas were side-lined, considered as overly subjective. It is only over the past couple of decades that the theorem has been rediscovered and widely applied thanks to the advent of modern computing power (Poundstone, 2019).

Pearl (1988) and Spiegelhalter and Lauritzen (1988) contributed to advancements in Bayesian theory through their development of computationally efficient ways to propagate and aggregate large numbers of probabilities that are essential to analyse complex inference networks. These have been vital to the development of software systems which are used to create and use BBNs (Schum, 2001). Nowadays, applications of Bayesian probability are used in almost every aspect of modern lives. Doctors, engineers and bankers use computerized Bayesian networks to aid their decision-making (Khakzad et al., 2011; McLachlan et al., 2020; Sanford & Moosa, 2012). Even email spam filters work on Bayesian principles (Wei, 2018).

BBNs have evidently been used in other sectors for many decades. The application of BBNs to climate adaptation, however, has been limited (de Nijs et al., 2014; Richards et al., 2013; Sanò et al., 2014). The ability of BBNs to support exploration of events that are not directly or currently observable, integrate multiple sources of data, and iterate over time, is advantageous for their application to climate adaptation (Catenacci & Giupponi, 2010; Sperotto et al., 2017).

### 7.2 Elements of BBNs

A BBN, according to Constantinou and Fenton (2018, p.19) is "a diagram which uses arrows to show how various factors -represented by nodes, influence one another." A BBN explicitly describes direct dependencies between a set of variables through the form of a directed graph and a set of node probability tables (Fenton & Neil, 2019). BBNs thus map cause and effect relationships between key variables being studied. Variables are represented as nodes in a directed acyclic graph (DAG) and dependencies depicted as edges between the nodes (Vogel, 2013). In summary, the following elements comprise a BBN:

- **Chance Nodes:** represent random variables within the system (represented as ovals in a BBN). Each chance node has an associated Conditional Probability Table (CPT), described below. Parents can be decision nodes and other chance nodes (Bayes Fusion LLC, 2020a).
- **Node states** are the different states a node may take (e.g. desirable and undesirable states) which can be either discrete (data which can be counted and only take specific values) or continuous (data which can be measured,

assume any numeric value and can be meaningfully split into smaller parts) (Cain, 2001).

- **Arcs** are links between nodes which represent causal relationships between the nodes. For description purposes, when there is a link from node A to node B, A is referred to the parent and B as the child (of A). Conversely, independencies are shown through missing arcs between nodes (Vogel, 2013).
- **Conditional Probability Tables (CPTs) -** sets of probabilities for each node describe the belief that a node will be in a particular state given the state of nodes that directly influence it, the parent nodes (Constantinou & Fenton, 2018). These are referred to as conditional probability tables or CPTs (Cain, 2001). CPTs define the probabilistic relationship between variables within a BBN.

  CPTs can be constructed from a range of information sources including (i) raw data collected by direct measurement; (ii) raw data collected through stakeholder elicitation; (iii) output from process-based models calibrated using raw data from direct measurement; and (iv) expert opinion based on theoretical calculation or best judgement (Cain, 2001). However there is not always data on the relationships between such variables and subjective expert judgement can be integrated to provide information on the strength of the dependencies between variables.

The different elements of a BBN are illustrated in Figure 7.1 which shows three nodes: A, B and C. In BBNs, C is referred to as the child of A & B. A and B influence the probability of C taking different states. Transforming this into a BBN requires the prior probabilities of A and B and the conditional probability of C (the probability of C given A and B). In Figure 7.1, A and B are conditionally independent, but C is conditionally dependent on A and B.

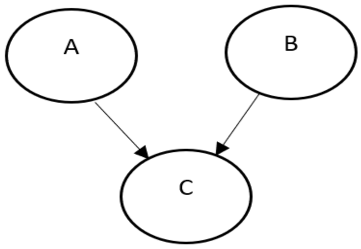



*Figure 7.1: Illustration of a directed acyclic graph*

An example of how a BBN may be applied is the Asia Network example proposed by Spiegelhalter and Lauritzen (1988) (Figure 7.2), which describes a diagnostic problem for tuberculosis or lung cancer. Conditions of the patient are illustrated by nodes with links between certain nodes indicating relationship and causality between the variables. The network allows the user to consider the presence or absence of different conditions represented in the variables, i.e., if the person is a smoker or not, to assess the likelihood that the condition may be tuberculosis or lung cancer. The BBN can therefore be used as a diagnostic to assess if the patient has tuberculosis or lung cancer which can help inform treatment.

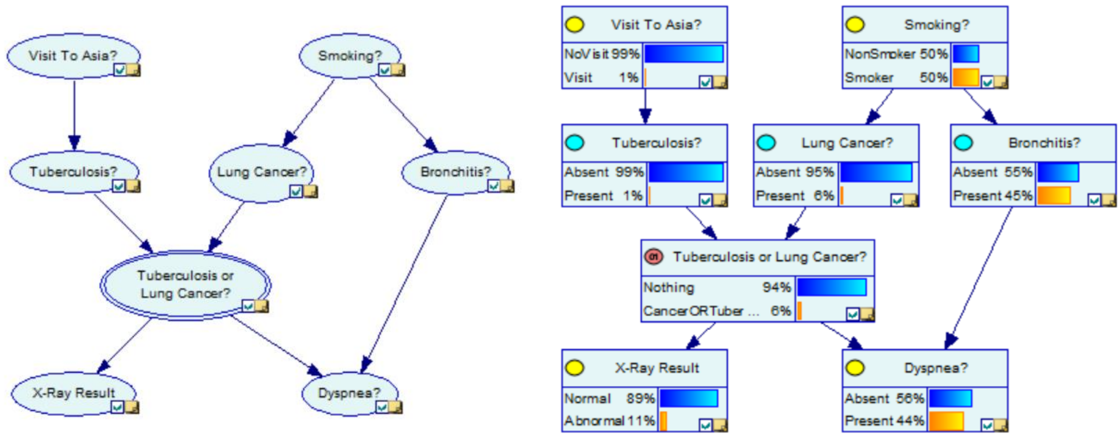



*Figure 7.2: Asia Network example BBN proposed by Spiegelhalter and Lauritzen (1988). BBNs may be viewed in icon form (as shown on left) or bar charts (as shown on the right).*

A BBN is a graphic representation of a problem and can therefore be used for multiple types of inference. Whilst the example in Fig 7.2 is a BBN used as a diagnostic, in other instances BBNs may be used for other purposes such as decision-making or options appraisal. According to Jakeman et al. (2006) the are several purposes for building a model of a system including: (i) a desire or need to increase qualitative understanding of the system; (ii) hypothesis testing; (iii) prediction including extrapolation from previous event; (iv) "what if" exploration and for; (v) providing assistance with management and decision-making. BBNs can provide support for all these purposes.

A BBN by itself does not support decision-making under uncertainty. This is because decision-making requires knowledge of the uncertainties in the studied system as well as insight on the potential decision options available and their different consequences (Renooij & Gaag, 1998). Howard and Matheson (2005) propose that influence diagrams, also known as Bayesian Decision Networks, are more tailored for decision-making. Within a BBN all nodes are uncertain "chance" nodes whereas in a Bayesian Decision Network or influence diagram, nodes which represent decisions can be distinguished as a "decision node" (drawn as a rectangle), and "utility nodes" (drawn as diamonds) which show how the outcome of interest can be maximised or minimised (Constantinou & Fenton, 2018). Decision nodes represent several possible decisions that can be taken and utility nodes represent the expected value and how this may change as a result of a decision (Pollino & Henderson, 2010). Choices in a decision node do not have associated probabilities. A utility node does have an associated table representing multi-attribute utility function. Figure 7.3 illustrates an example network with a decision and utility node to support decision-making relating to financial investment decisions. The network illustrates a business decision concerning investment of a sum of money into an uncertain business venture.

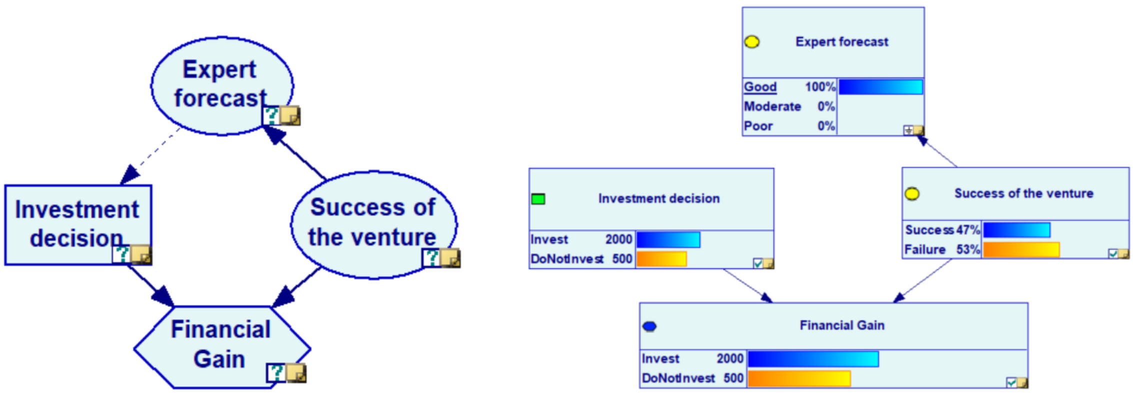



*Figure 7.3: Example of a Bayesian Decision Network or Influence Diagram in both icon (left) and bar chart (right) format. The decision node, investment decision, is represented by a rectangle and the utility or value node, financial gain, is represented as a hexagon. The example BBN was developed by Bayes Fusion LLC (2020a).*

Bayesian Decision Networks illustrate decision problem and aim to identify the decision options with the highest expected gain (or utility). These types of networks are seen as beneficial because they can be used to explore scenarios to find the optimal decision or combinations of decisions (Catenacci & Giupponi, 2010). Because decision-making is the focus of this research, I focus on studying the value of Bayesian Decision Networks. A Bayesian Decision Network can also be referred to as an influence diagram or in some cases still as a BBN. Within this thesis, BBN is used to cover Bayesian Decision Networks.

Advantages of BBNs (to support decision-making) that were identified as relevant to this research included: (i) ability to address situations of missing data; (ii) incorporates both causal and probabilistic elements and so are appropriate for combining prior knowledge with data; and (iii) can be used to model causal relationships to further understanding of problem and begin to predict consequences of interventions (Nadkarni & Shenoy, 2004). There are, however, limitations of BBNs. For example, BBNs may discretise continuous variables, as in the case of this thesis. When variables are discretised into few states, this may lose granular detail on relationships within the network (Aguilera et al., 2011; Nojavan et al., 2017). Secondly, there are no feedback loops with BBNs, as they are acyclic, so they are not appropriate for modelling dynamic systems with feedbacks (Uusitalo, 2007). Despite these drawbacks, the potential to aid vigilant decision-making by supporting data collation and review of potential adaptation options, BBNs were seen as suitable for this research to explore further.

### 7.3 Methodology used in BBN Study

The remainder of this section details how a BBN was created and applied in this study. BBN development protocols were consulted for guidance on best practice. Steps undertaken were influenced by guidance in Cain (2001), Marcot et al. (2006), and Chen and Pollino (2012) and aligned with the good environmental modelling practice framework proposed by Jakeman et al. (2006). A substantial amount of the published literature on BBNs, however, presents case studies, with varying levels of detail provided on the steps undertaken. Due to the opacity of many studies, I draw heavily on Cain (2001) as this presents a detailed approach to constructing BBNs. Research Objective Two explicitly sought to explore the usefulness of BBNs to city-level adaptation decision-making in practice. This research therefore focuses on applying the method of BBNs (to climate change) as opposed to extending it. This also presents challenges to reference relevant literature, as published articles are often about theoretical development of BBNs rather than delivering BBNs in practice to support decision-making.

The BBN was created in three phases. Phase One focused on constructing the qualitative network, where the goal of the BBN was defined, stakeholders identified and consulted, and the qualitative network developed. Subsequently, Phase Two was the quantitative phase where the BBN variable states were defined and CPTs were populated using expert elicitation. Phase Three involved options analysis, sensitivity analysis and assessment of the BBN usefulness. Each phase will be described in turn and is summarised in Figure 7.4. Notes and observations from participant observation research, conversational interviews with the adaptation lead and feedback sessions with experts consulted for expert elicitation, as well as steps undertaken to build the BBN and additions made, were recorded in a research diary.

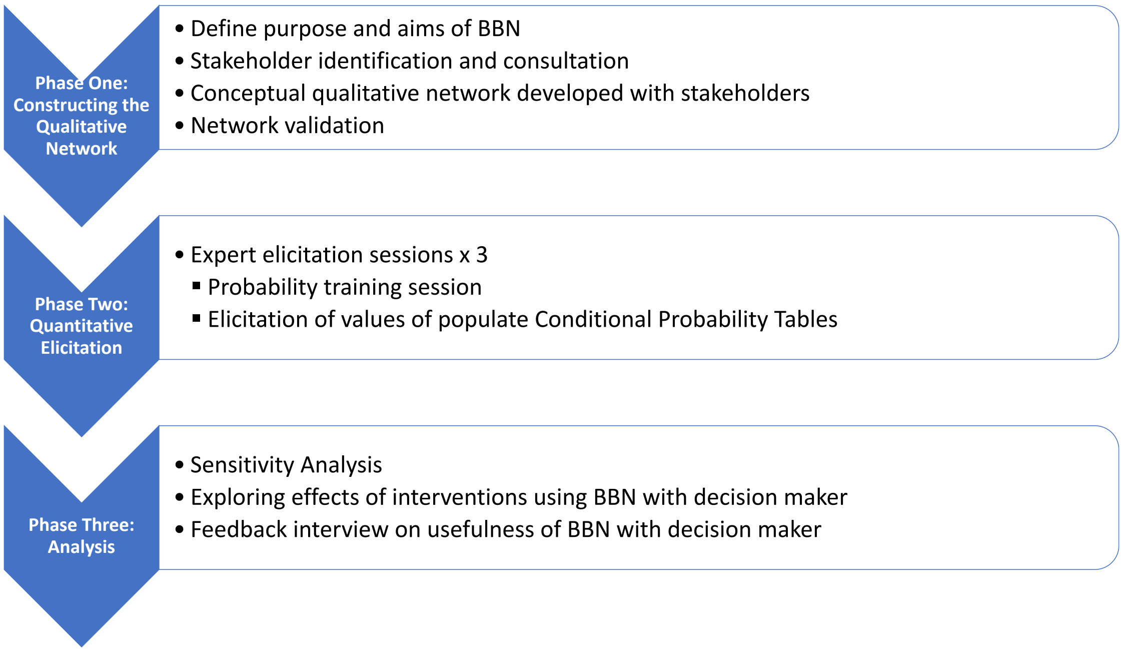



*Figure 7.4: Process employed to construct the BBN Network– image authors own*

### 7.3.1 Phase One – qualitative structure

The first phase of BBN development involved defining the problem, identifying stakeholders, and constructing the qualitative network. Initial activities needed to construct a BBN include problem scoping, whereby the challenges intended to be addressed are identified (Phan et al., 2019). To ensure there was legitimate buy-in on the aim of the BBN, the adaptation lead (the main decision maker) was consulted with and an agreed upon goal was developed. The defined goal was to construct a network which supported decision-making to enable (pluvial) flood resilience in Glasgow city centre.

Next, stakeholders were identified and consulted. When selecting stakeholders to populate the BBN, Cain (2001) suggests stakeholders should possess good local knowledge, live or work within the geographic area being considered and be available for consultation in all workshops. Given that the network focused on a specific geographic area and required expert input, this advice was heeded. The ten stakeholders influenced the BBN development were all associated with the Climate Adaptation Taskforce (described in Section 6.1). Within this study, the network structure was developed iteratively over four main stages (as shown in Figure 7.5).

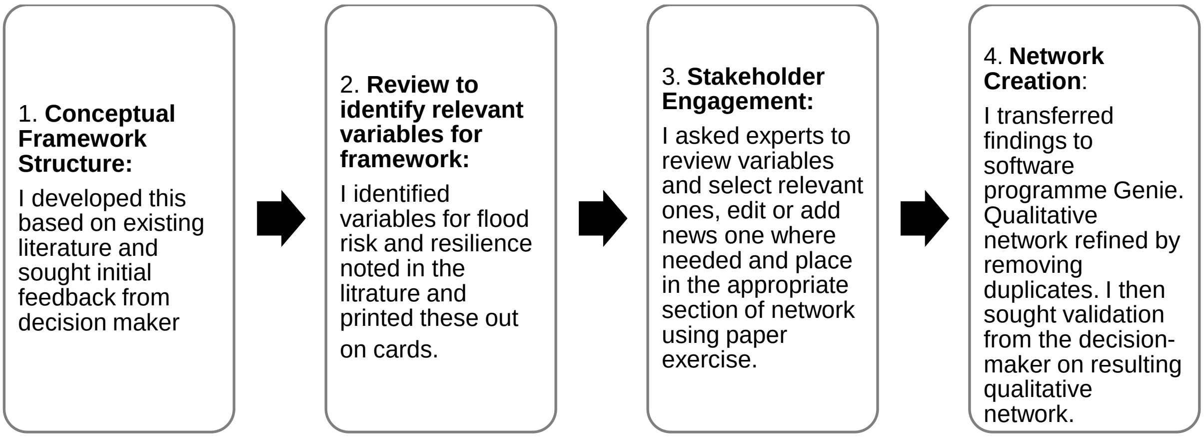



*Figure 7.5: Summary of steps undertaken in Phase One – qualitative structure. Image summarises process used to generate qualitative structure for Glasgow flood resilience BBN*

Firstly, I developed a structure to guide the network development. The request from the decision-maker was to use resilience as a framing (given the council's push for resilience following 100RC participation as discussed in Section 6.1). The term resilience is interpreted in relation to climate resilience within this chapter to mean well adapted and prepared for current and future climate impacts. Existing conceptual interpretations of climate resilience were identified by reviewing climate adaptation and resilience literature. The elements of hazard, exposure and adaptive capacity (discussed in Section 3.1) are common to many climate change adaptation and resilience framings including Klein et al. (2003), Lindley et al. (2011) and Oppenheimer et al. (2014). Due to their fundamental nature contributing to climate risk and resilience and prominence in the literature, these concepts were selected as core components of the framework. This also meant that the BBN would align with the IPCC's AR5 conceptual framing of climate risk, which helped increase the network's perceived relevance or salience to the decision maker.

In addition, I proposed to incorporate the resilience of public sector institutions as a component of the conceptual framework. This component was suggested due to its importance noted in the literature and in practice within GCC. For instance, Berkhout (2012) and Oberlack (2017) stress the importance of public sector institutions in preparing for and adapting to climate change. Tyler and Moench (2012) also include institutions within their Urban Climate Resilience Framework, due to the role institutions play in influencing agents and systems interactions in responding to climate stresses and shocks. In addition, GCC consistently spoke of the need to ensure they and their arm's length organisations (ALEOs) were resilient to climate change, to ensure continued service provision. As highlighted in Section 6.4.1.3, there was a desire to get their own 'house in order' at the city council level. Furthermore, Chapter 6 highlighted that a range of influencing factors can affect climate adaptation decision-making, which will thus have consequences on the resilience of the city. Given also that the network was intended for use by GCC, a component that focused on internal drivers of resilience to help identify actions for GCC and it's ALEOs was identified as beneficial.

The component of adaptation interventions was included to operationalise the framework for use in appraising adaptation actions. The interpretation used within this thesis is that flood resilience is influenced by exposure, adaptive capacity, the resilience of public sector institutions and adaptation actions (as shown in Figure 7.6). Within adaptive capacity, the ability to prepare, react, and recover is captured. Given that this research is interested in the value of BBNs to aid adaptation decision-making, a simple framework was used for initial testing. This framework was firstly shared with the decision-maker, who requested the concept of sensitivity (which had originally been included) be removed given that she felt her adaptation plan could not influence sensitivity of population and that it was potentially too academic. Additional feedback was sought from stakeholders via an engagement process. For further insight on interpretations and conceptualisation of flood resilience in the literature, see McClymont et al. (2020) and Kuang and Liao (2020).

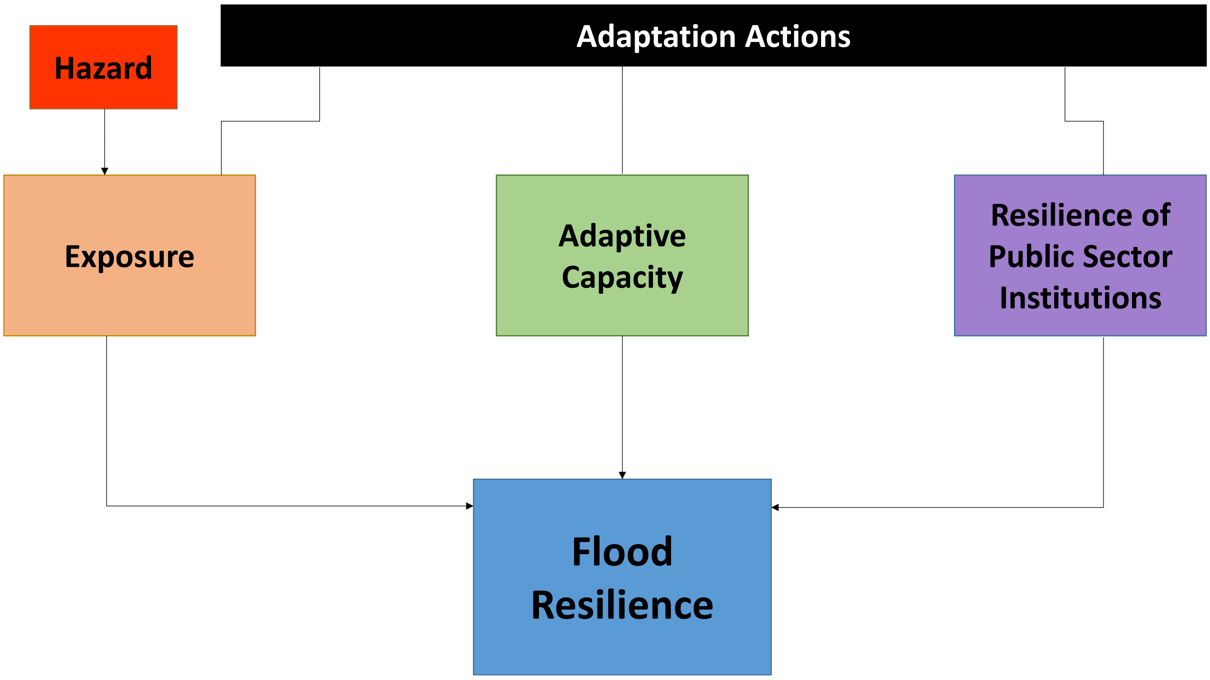



*Figure 7.6: Components of conceptual framework identified from literature. This framework provided the overarching structure to influence the development of the BBN (which utilises this structure)*

The next stage involved stakeholder engagement. Stakeholder feedback was sought on: (i) the overarching framework structure as a way to represent flood resilience in Glasgow; and (ii) their input to identify variables underlying each component. The process to identify and structure network was informed by Sanò et al. (2013). This process used an A0 print out of Figure 7.6 to visualise each component of exposure, adaptive capacity, and public sector institutional resilience. Smaller cards were also provided which listed indicators used for flood resilience identified in other studies (Lindley et al., 2011; Scottish Government, 2015). Stakeholders participating in Climate Resilient Glasgow's climate adaptation strategy workshops were asked for their feedback. To identify variables, stakeholders were prompted with the following statements:

- "*Identify variables that directly influence Glasgow's resilience against pluvial floods generally"*
- *"Identify the variables that directly influence Glasgow's adaptive capacity (to pluvial floods)"*
- *"Identify the variables that directly influence Glasgow's exposure to pluvial floods*"
- *"Identify the variables that influence public sector institutional climate resilience in Glasgow"*

Next a follow up statement was offered, to prompt exploration of next layer of direct causality. Stakeholders were requested to:

- *Identify the variables that directly influence the primary-level variables identified*

Upon identification and selection of the variables, the influence relationships between nodes were then identified by stakeholders by drawing the direction of influence where they felt confident. It was requested that parents (of the same child) be kept to a maximum of three variables (as much as possible). Stakeholders were also instructed to make the primary variable independent from one another so that the states of one these primary variables were not influenced by or had influence on another.

States of nodes were also specified. It was recommended that experts use desirable and undesirable as the starting two states. This was driven by the fact that two states, one positive one negative, would keep the CPTs manageable for subsequent elicitation. States were also specified based on data availability (where applicable) and aligned with regulatory and decision-making thresholds as recommended by Pollino and Henderson (2010). Discrete variables were used within the BBN. It was found continuous variables were not appropriate given the problem setting and the challenges in mixing continuous and discrete variables within one network. The selection of discrete states aligns with Fenton and Neil's (2018) proposal that discretising a continuous variable, not only makes the process simpler, but there are also little loses in efficacy. In total, ten individuals participated and provided feedback on the proposed structure, identified relevant variables or nodes and suggested relationships and dependencies between the variables.

The result of Phase One was a qualitative BBN, with each child node having a maximum of three parents, most with only two discretised states. Once the initial qualitative structure had been created by stakeholders, it was then refined to ensure ease of use and communication and interpretation. It is important to simplify BBNs where possible, so they are more easily understood and also to ease elicitation burden and make it easier to complete CPTs at later stages (Cain, 2001). There is, however, a need to not lose any of the detail regarding the relationships within the network.

The first way to simplify a BBN is to decide which factors are necessary to represent in the BBN and which do not need to be. For example, a factor that is less likely to affect the outcome or be altered, may not be needed in the network (Cain, 2001). This was decided by me the researcher. I simplified the structure by creating conditionally independent statements to remove places which had multiple arcs. For instance, I removed duplicate cause effect structures and duplicate nodes. I streamlined the BBN by removing intermediate variables, where possible to ease elicitation burden. As Fenton et al. (2007, p.1420) state “The conditional independence assertions about the variables, represented by the lack of arcs, reduce significantly the complexity of inference and allow the underlying joint probability distribution to be decomposed as a product of local conditional probability distributions (CPDs) associated with each node and its respective parents.” I recreated the hand drawn qualitative networks using the software programme, Genie (Bayes Fusion LLC, 2020a).

Validation of the network structure is a key step in the process of BBN development, particularly for instances where the outcome of the model cannot be directly observed in real life (Pearl, 1988). Face validity is an approach to validity proposed by Pitchforth et al. (2014) which involves showing an expert the model structure, node discretisation and parameters and asking if these reflect their opinion. This method was used in this study given the oversight of the adaptation lead as the main decision maker with knowledge across the BBN sections. The adaptation lead, the main decision maker in charge of adaptation, reviewed the network and approved the structure verbally.

### 7.3.2 Phase Two – quantification of network

Quantifying a BBN involves populating the CPTs underlying each node. CPTs express the probability that the node will be in particular states given the states of its parent variables (Cain, 2001). As such, the data should describe how a node changes in response to alteration to its parents (Sen, 2016). This study used expert elicitation to identify values for the CPTs, as the necessary data did not exist for many of the nodes due to uncertainty associated with climate change adaptation (such as not knowing how climate impacts will affect society or inter-connected infrastructure systems, the extent of climate change or the implications of taking different adaptation actions) (Preston et al., 2013).

It is necessary to develop an elicitation process to support experts to provide probabilities. The field of structured expert judgement, eliciting expert knowledge as a form of scientific data, has been informed by leading thinkers and proposers of expert elicitation protocols including O'Hagan et al. (2006), Cooke and Goossens (2008) and Hanea et al. (2018). There is no singular universally accepted protocol for elicitation of probabilities, however reviews of best practice for eliciting and utilising expert judgements include Cooke (1991), Morgan and Henrion (1990) and O'Hagan et al. (2006). Common stages of these elicitation protocols include: (i) motivating (which refers to outlining goals of study to the experts); (ii) making participants aware of cognitive bias and searching for motivational bias; (iii) structuring where one should use unambiguous definitions and rigorous and testable judgement; and (iv) conditioning where one identifies reasons and relevant factors and encourages consideration of a range of situations (Morgan & Henrion, 1990; Spetzler & Von Holstein, 1975).

Expert elicitation provides a way to quantify the uncertainty about unknown parameters (Colson & Cooke, 2018). Methods for expert elicitation range from engaging an individual expert to identify their best estimate to a formal process asking multiple experts and combining their views into probabilistic judgements. Whilst the information is subjective, in situations where empirical evidence is limited which was the case for GCC, non-existent or difficult to access, knowledgeable experts may be a good resource of evidence and their value judgements can be useful (Colson & Cooke, 2018; Morgan et al., 2001; Morgan, 2014).

Expert judgement elicitations have been used in relation to climate adaptation studies. Examples include Morgan et al. (2001) which used expert judgement to understand climate change impacts on forest ecosystems, Varis and Kuikka (1997) who examined climate change impacts on surface waters and by Doria et al. (2009) to define metrics of successful adaptation. It is stressed that expert judgement is not a substitute for data but instead a way to support decision-making before all the evidence is available and therefore should sit within a cycle of adaptive management (Morgan et al., 1990; Pollino & Henderson, 2010).

The experts involved in expert elicitation in this study were experts in their respective fields (e.g. emergency response, flood risk management and adaptation) but not necessarily experts in probability theory. Therefore, the elicitation process was designed as simple as possible to aid experts in communicating their beliefs effectively and accurately. The experts were able to provide insight based on their lived experience and professional history to populate CPTs and thus address the limitations in existing quantitative data. Within this study, three experts were used to quantify the CPTs of the BBN, in relation to the three subsections of the network (exposure, adaptive capacity and resilience of public sector institutions), as demonstrated in Table 7.1.

*Table 7.1: Summary of Expert Elicitation Sessions for BBN including purpose of elicitation and time taken*

| Expert | Background /Role | Model Section & # of nodes quantified | Time of Elicitation Session |
|---|---|---|---|
| 1 | Emergency response / Blue light responder | Adaptive Capacity | 1hr 30 mins |
| 2 | Flood risk management policy advisor | Exposure | 2 hr 40 mins |
| 3 | Climate adaptation specialist working for adaptation intermediary | Climate adaptation maturity | 1 hr 50 mins |

The elicitation protocol followed the below steps:

- **Motivating the expert -** Explaining the expectation of the subjective knowledge and why experts were being engaged. It was explained to the experts that their responses were requested to represent their subjective belief of the likelihood of events or circumstances.
- **Training the expert -** explain style of questions used. I guided experts through a probability exercise and example questions (exercise in Appendix VIII).
- **Elicitation** - Experts completed the questionnaire via verbal response. Experts assigned percentages to the CPTs demonstrating their belief in the strength of specified relationships (example structure shown in Appendix IX).
- **Feedback -** The end of each expert elicitation session included interviewing the experts on how they found the process (questions available in Appendix X).

When eliciting values from multiple experts, aggregation must be considered. Aggregation may occur behaviourally through consensus, through discussion, and deliberation, as proposed by (O'Hagan et al., 2006). Additionally, aggregation can be conducted mathematically whereby individual estimates are combined given a certain mathematical function as proposed by Cooke (1991). Often expert elicitation involves eliciting values from multiple experts with a range of backgrounds and expertise, however the BBN necessitates the input of a single probability distribution for a parameter rather than a set of distributions from multiple experts (Colson & Cooke, 2018). This was not necessary in this study as different experts were asked to populate CPTs for different sections of the BBN based on their expertise and as such aggregation was not required.

Expert elicitation was conducted via one-on-one interview sessions with experts providing estimates for CPTs individually. This methodological choice was made, instead of a group workshop session to obtain consensus and populate CPTs collectively. This decision was due to separate sections or components of the BBN dealing with different areas of expertise each stakeholder possessed, and the BBN components being treated discretely. Whilst the BBN structure was based on collective beliefs (input from ten stakeholders iteratively together), the CPTs were populated based on individual stakeholder beliefs. This follows the methodology used by Sanò et al. (2013).

Multi attribute utility (MAU) theory was then used in this study as a way to aggregate the different components of the BBN (exposure, adaptivity capacity and resilience of institutions) into an overarching flood resilience index. MAU theory enables integration of subjective and objective data within a common scale or index which can be used within decision-making processes (Dyer, 2005). Multi attribute decision theory supports decision makers to make trade-offs between several attributes (Bedford & Cooke, 2001). It was anticipated that the complexity of the decision-making problem could be eased through eliciting utility functions for various attributes separately and then combining them into one multi-attribute utility function. A local score was used.

Validation of the BBN is important for ensuring elicited expert judgements accurately reflect reality and provide an empirical control (Colson & Cooke, 2018). Unfortunately, it is difficult to validate expert judgement when the object of interest in not visible in practice, as is the case in many of the nodes in the developed BBN. This is a limitation of BBNs when applied to climate adaptation, however, it can be addressed by updating the network with information as it becomes available.

### 7.3.3 Phase Three – Analysis

The third phase of BBN development was analysis. This consisted of using the BBN for options analysis and sensitivity analysis. Each type of analysis is summarised here.

The BBN was used to analyse the effect of different adaptation options. An important attribute of BBNs is that they allow the researcher to carry out "what if" experiments by altering individual variables and seeing how this affects the overall model. Within the created BBN, one can change decision nodes and then investigate the effects different decisions (or adaptation actions) has on the objective nodes. BBNs can thus be used for analysis by altering states of selected nodes and observing the effect it has on other nodes. A BBN encodes a joint probability distribution across all nodes. As such, every time a node value changes, the joint distribution is changed through iterative application of Bayes' theorem (Cain, 2001). In this study, I applied the BBN to assess the impact of various adaptation actions to enhance resilience to pluvial flooding in Glasgow. Evaluation of the different actions within the BBN was done solely with the adaptation decision maker at GCC, as they had oversight of the overarching adaptation action plan.

Sensitivity analysis was also undertaken on the developed BBN. Sensitivity analysis determines how “sensitive” a model is to changes in the value of parameters of the model as well as changes to the model structure. The process illustrates behaviour changes in relation to certain variables to identify key leverage points (Breierova & Choudhari, 1996). A sensitivity analysis illustrates the contribution of individual variables on the overall performance or outcome of the target variable. An aim of analysis of BBNs is often to compute the conditional probabilities of a target node in the network (Castillo et al., 1997). For the purposes of this research, it was important to understand the sensitivity of the conditional probabilities of nodes that influence overall flood resilience utility.

A common method of sensitivity analysis is to alter the parameter values and then use an evidence propagation method to monitor the effects of these changes on the conditional probability tables. This is a brute force method which is computationally intensive (Kwan et al., 2011). Due to the manageable number of nodes in the created BBN, this method was employed. The following steps were used for sensitivity analysis in this study:

1. Each parameter was selected one by one to be varied
2. Conduct sensitivity analysis for each variable individually, using two parameter values (low and high).
3. Identify effect of changes on dependent nodes (society exposure, built environment exposure, exposure, ability to prepare, react, recover, adaptive capacity) and record
4. Summarise and present results

This section summarised the methodology used to develop a BBN. The findings from BBN creation are presented in Chapter 8. The next section introduces the methodology used to develop a QPN.

## 7.4 Qualitative Probabilistic Networks

In creating a BBN for pluvial flooding in Glasgow and reviewing the usefulness of BBNs for climate adaptation decision-making, I was able to identify several challenges and limitations of the BBN approach (presented in Section 8.4). As a result of the noted limitations, a second study was undertaken using QPNs to explore whether some of the challenges identified (namely elicitation burden) could be overcome via a qualitative rather than quantitative approach. The remainder of this section provides an overview of QPNs and then outlines the methodology employed to create an adjusted QPN for heatwaves in Glasgow in this thesis.

QPNs are qualitative abstractions of probabilistic or Bayesian networks (Wellman 1990). QPNs are therefore applicable where numerical conditional probabilities (as needed for BBNs) are not available or necessary for the problem situation. As QPNs contain qualitative probabilistic relationships as opposed to numerical relationships (as in a BBN), QPNs require less effort than numerical specification of a BBN (Druzdzel, 1996). According to Biedermann and Taroni (2006 p.165), “Generally, the construction and use of a QPN demands less effort than a numerically specified B[B]N.” It is suggested by Kwisthout and Tel (2006) that QPNs have been proposed as a qualitative abstraction of probabilistic networks to overcome the difficulty of eliciting probabilistic information from experts.

QPNs have been applied across a variety of fields. Studies on the application of QPNs are available in the fields of computer sciences (De Campos et al., 2009), technology (Balamuralidhar, 2013) and medical diagnosis (Beumer, 2006). For instance, Bolt et al. (2005) constructed QPNs to support real-life decision-making in the field of oncology and Karanam et al. (2021) studied qualitative influences to further understand the risk of gestational diabetes. There are, however, no available studies to date of QPNs applied to climate adaptation, that have been found via a review of the literature. Thus, this thesis seeks to address this gap by exploring how QPNs could be used to support city-level climate adaptation decision-making.

### 7.4.1 What is a QPN?

QPNs are directed acyclic graphs which provide a representation of variables and their dependencies (Biedermann & Taroni, 2006). Within a QPN, qualitative relationships relating to influences and synergies are used instead of numerical relations. Qualitative influences describe the direction of the relationship between two variables (i.e. a parent and a child node), whilst qualitative synergies illustrate interactions amongst influences (i.e. between multiple parent nodes) (Wellman, 1990).

QPNs illustrate types of influence between parent and child nodes within the network. Whilst QPNs have a similar structure to BBNs, instead of numerical probability distributions, QPN represent signs of influence among variables in the network (Druzdzel, 1996). QPNs summarise the influences between variables in a network by a qualitative sign, denoting the direction of the effect, i.e. positive or negative (Bolt et al., 2005; Kwisthout & Tel, 2006). A qualitative influence between two variables demonstrates how observing a value for one affects the probability distribution for the other (Van Der Gaag & Helsper, 2004). According to Parsons (1995, p.427), "Whereas in probabilistic networks, the main goal is to establish the probabilities of hypothesis when particular observations are made, in qualitative systems the main aim is to establish how values change rather than what the values are. Since the approach is qualitative, the size of the changes are not required. The only consideration is whether a given change is positive, written as [+], negative [-] or zero [0]."

The different type of influences or causal relationships which can be captured within a QPN (represented visually via different arrowheads on the arc between nodes and/or with annotations) include:

- **Causes**: These are influences which make effects more likely. This is where the parent node causes the child node. For example, smoking could be a parent node which makes the child node of lung cancer more likely. These are positive (or +) influences on another variable as the direction of influence makes the child node more probable.
- **Barriers**: These are influences which have a negative effect (-) or make the effect less likely. For example, regular exercise and probability of heart disease.

- **Uncertain**: In addition, QPNs may capture uncertain relationships, noted as [?] (Druzdel, 1996). This is where there is uncertainty in the type of influence occurring.

Insight into these causal influences can aid understanding of the system. Because QPNs do not contain numerical conditional probabilities like in BBNs, they are not adequate to determine the exact probability distribution of variables. However qualitative relationships can help deduce relative likelihood constraints which can support decision-making processes (Wellman, 1990). According to De Campos & Ji (2011) qualitative influences define some knowledge about the state of a variable given the state of another.

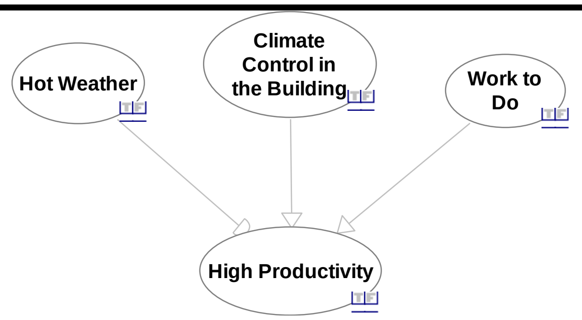
In addition, the strength of influences can be noted, which also helps improve QPN outputs by providing additional information. Renooij & Gaag (1998) proposed extensions to the basic formalism of a QPN to enhance the QPN by adding a notion of strength to be able to resolve trade-offs between conflicting influences (for instance where one is positive and the other negative). Renooij (2001) provided a methodology for how to use verbal expressions of probability during elicitation whereby the arcs in the network are annotated to indicate the direction change in probability for a variable at end of arc, given changes to values at the other end of the arc, as well as the strength of this change. The arcs between variables can illustrate the strength of these relationships via variable widths, with the thickness of each arc representing the strength the parent node influences the child node (Bayes Fusion LLC, 2020b).

A second type of relationship which can be represented in a QPN is that of synergies. The previous section introduced influences which denotes the type and strength of causal relationship one variable has on another. Synergies, however, describe the interactions amongst influences (Biedermann & Taroni, 2006). Synergies demonstrate interaction among the influences between three nodes (Van Der Gaag & Helsper, 2004).

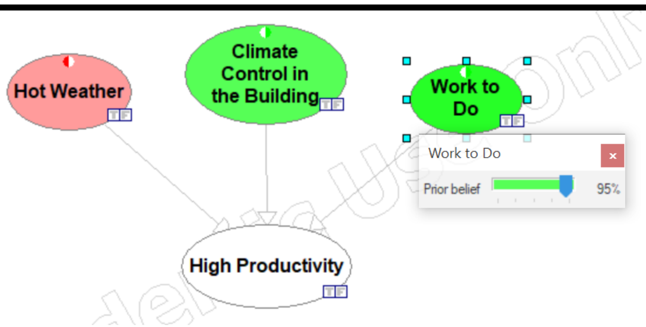
The information represented within QPNs, in terms of influences, strength of relationships and synergies, can be used to aid system understanding and support decision-making. QGenie is a computer programme that supports the creation of

QPNs (Bayes Fusion LLC, 2020b). The programme enables the calculation of manipulation of nodes within the network. By setting states of different nodes, it is possible to observe the effects. This is because qualitative belief propagation maps the effect of an observation on other variables by propagating the sign of change from evidence through the entire network (Druzdzel, 1996). To illustrate the various components of a QPN and how QPNs may be constructed and applied, a case study example is presented. Figure 7.7 shows the different steps involved in creating a QPN to understand high productivity in an office, and how this is influenced by hot weather, the availability of climate control in the building and work to do. This example is based on the guidance by QGenie creators in Bayes Fusion LLC (2020).

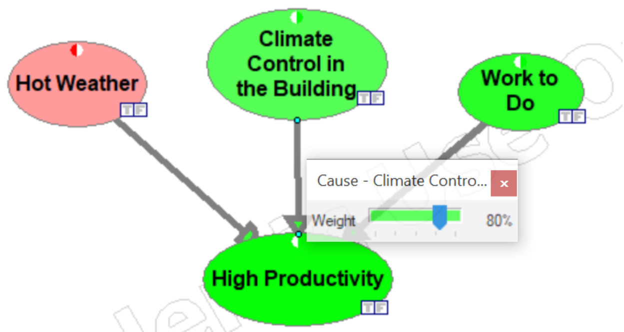
**1.Identify variables and types of influence.** Influences between variables, or nodes, may differ (in terms of positive or negative effects) and are represented via varying arrow heads. In this example hot weather is a barrier to high productivity (has a negative influence), whilst climate control and work to do are causes (have positive influences). Variables are binary with the two states being true or false, or desirable and undesirable.




**2.Set prior probabilities of parentless nodes.** A numerical property of a QPN is node beliefs or probabilities. These express the prior probability of the proposition expressed by the node for those nodes with no parents in the QPN (Bayes Fusion LLC, 2020b). The prior probability of (degree of belief in) the proposition can be altered via a slider, as shown. In this example it is set that there is 80% chance that hot weather is occurring, 90% chance that climate control is operating in the building and 95% of the time there is work to do. The gradient of each colour represents the degrees of truth of the proposition, or the probability of the state. Desirable states are illustrated via green colour and undesirable with red colour.




**3.Specify weight of influences.** Interaction probabilities or weights illustrate the strength of causes in their ability to influence the effect (Bayes Fusion LLC, 2020b). The weight of the influence can be altered via a slider, as shown. For instance, in the example a weight of 80% is specified to represent the barrier, or negative relationship between Hot Weather and High Productivity. The weight of the relationship between Climate Control in the Building and High Productivity is also set to 80% meaning that there is 80% chance that the productivity is going to be high, if the weather is hot, the climate control is present in the building and there is work to do. The QPN can then display the links between nodes (i.e. arcs) with variable width to represent the varying weights of their influence.




**4. Undertake analysis.** Specific nodes within the network can be designated as the focus of analysis. Within this example, the focus was on High Productivity. The QPN can be used to pose questions. For instance, one could ask "*What is the expected impact on productivity, of failure of the climate control in the building on a hot day with normal workloads respectively*?" This can be demonstrated within the QPN by telling the network that Climate Control in the Building has been observed to be false. This is illustrated by change to a red colour and F symbol in bold on node. Nodes can be specified as observable and/or manipulable and the QPN can assess alterations to the nodes. This supports the estimation of 'most effective actions'. Such analysis can also be done manually by altering states of nodes in the network and observing outcomes on probability distribution, as shown in pie chart image and table.

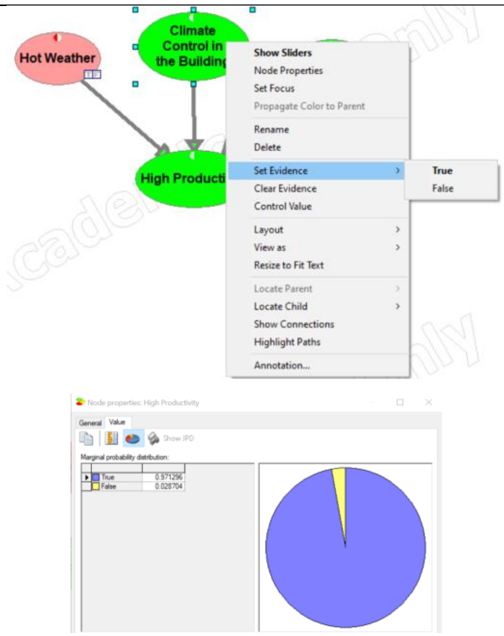



*Figure 7.7: Example of steps involved in developing QPN in QGenie using example provided by (Bayes Fusion LLC, 2020).*

My research aims focus on bridging the gap between researcher and practitioner for the adoption of the methods described within this thesis in the context of climate change adaptation. As such this thesis does not intend to develop new theoretical methods, nor provide a deep mathematical evaluation of the methods presented. The contribution of this thesis relates to assessing the value of the method in the specific context of climate adaptation decision-making (as opposed to conceptual development). As such I have not interrogated the underlying mathematical functions. I recognise that my understanding of the mathematical calculations being used within the QPN method are thus limited. As such, while I collected data relating to the QPN, I do not feel comfortable or confident presenting the quantitative analysis element of the QPN.

Furthermore, it is the qualitative network structure which was found to be the most beneficial to users, the object of study for my thesis (as described in Chapter 9). QPNs were selected given their qualitative nature, accessible visualisation, and inclusion of type of influence, as well as strength of influences and synergies between influences. These details were relevant to the study given a need to understand the co-benefits of actions and the benefits of taking multiple actions together. QPN literature focuses heavily on the mathematical underpinnings of the method, more so than on how the method can be used in practice. I used my contextual insight and experience to adapt the QPN methodology to fit my research setting. By this I mean, that a QPN is developed, including the influences and synergies between variables, however it is used qualitatively. For ease, I will refer to my adjusted QPN as a QPN for the remainder of this thesis

### 7.5 Methodology used in QPN study

The methodology adopted was heavily influenced by Renooij (2001) as this was one of the few resources which articulated the steps undertaken to develop a QPN. The QPN was constructed via continuing action research with GCC from September 2019 to February 2020 on the topic of heatwave risk and resilience. This topic was selected to explore a separate challenge compared to pluvial flooding studied via BBN and responded to demand from decision-maker. The following section outlines the three phase QPN development process of: (i) identifying QPN variables and initial structure;

(ii) identifying influences and synergies and (iii) using QPN to analyse options. The resulting findings are presented in Chapter 9.

### 7.5.1 Phase One: identifying QPN variables and structure

The first phase of the QPN development process was to identify the variables or nodes for the network. This was achieved via an interactive workshop in November 2019. The workshop exercises and discussions were centred around the IPCC AR5 climate risk framework, similar to the framework used to develop the BBN (described in Section 7.3.1). Minor alterations were made to the previous structure used in the BBN study, including the removal of the resilience of public bodies section. This was because it was felt that this was less relevant with the stakeholder group used to create the QPN, as it extended beyond just public sector. In addition, the content and learning from this section of the BBN on flood resilience could be re-used in relation to QPN on heat resilience, if desired, given transferability of nodes (resilience of public sector institutions component was not hazard specific).

Guided by the climate risk conceptualisation of IPPC in AR5 (IPCC, 2014), the QPN was structured in a similar way; focusing discussions around hazard, exposure, sensitivity, adaptive capacity and vulnerability, as shown in Figure 7.8 (and further described in Section 3.1). The variables underlying the network were identified by stakeholders at the workshop. Instead of providing participants with potential variables (as the BBN study did), all variables were proposed by the workshop participants themselves because indicators of heat risk or resilience in Scotland were not available in the literature.

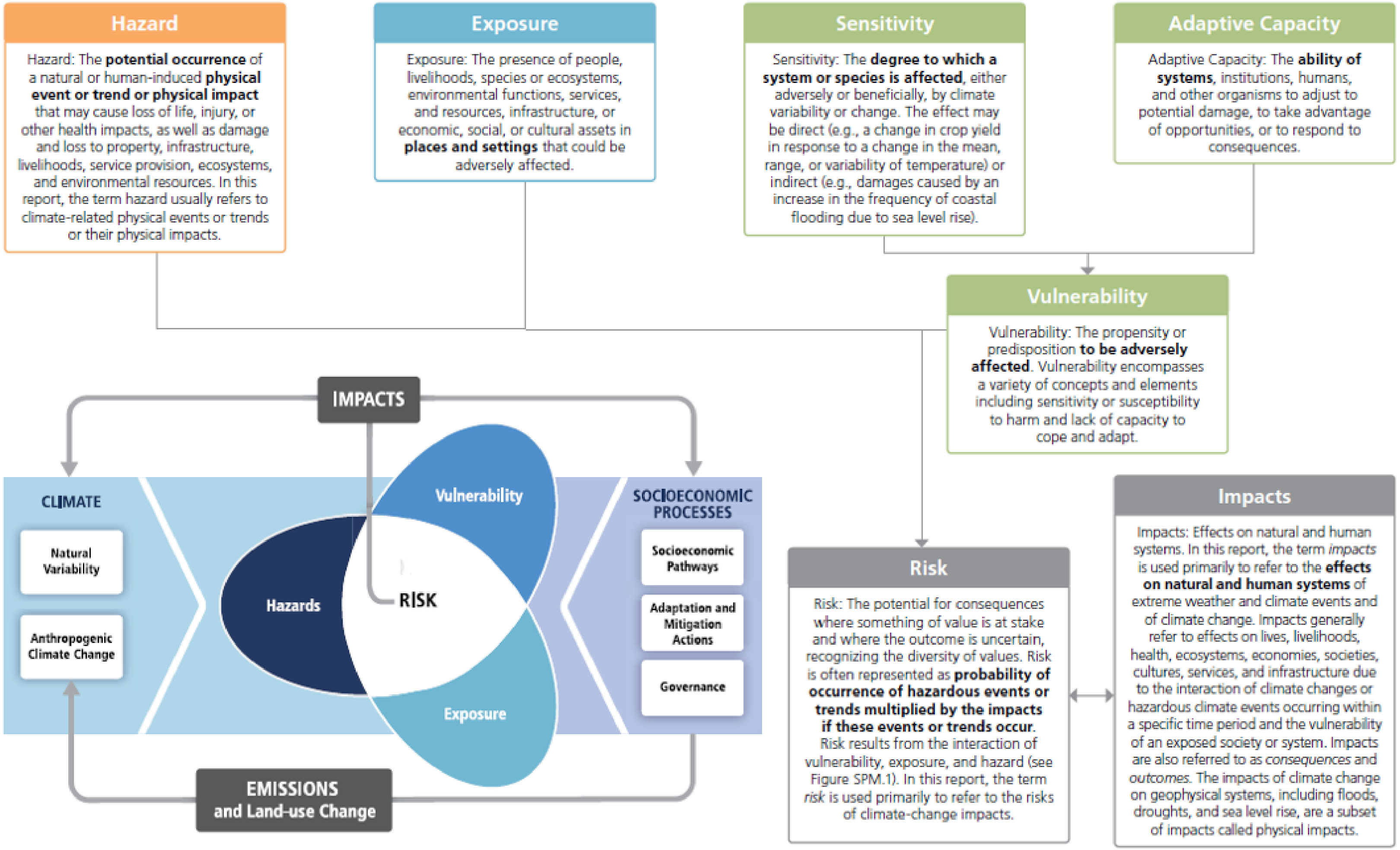



*Figure 7.8: Climate risk conceptualisation of IPCC AR5 WGII and IPCC definitions of key terms. (Source: IPCC, 2014)*

There were 12 stakeholders who contributed to the development of the QPN by attending workshops. Stakeholders represented different GCC departments (circular economy, education, transport, and Sustainable Glasgow), as well as arm's length organisations such as City Building Glasgow, charities like CEMVO, the partnership Climate Ready Clyde and academics from Glasgow Caledonian University, attended both workshops. These individuals were identified by GCC's adaptation lead as key stakeholders as their role's related to or contributed to the development of GCC's adaptation strategy and action plan.

Given that stakeholder's work related to adaptation but in some cases tangentially so, meaning not all were experts, an introductory knowledge exchange was incorporated into the first workshop. To ensure a basis of knowledge across participants, two presentations on heatwave risk to Glasgow were provided by an adaptation practitioner leading regional adaptation work in Glasgow City Region for the Climate Ready Clyde initiative and an academic researcher on the topic, a professor at Glasgow Caledonian University. I also provided a presentation on the key terminology that would be used in the workshop, namely hazard, exposure, sensitivity and adaptive capacity. After the presentations, workshop attendees were prompted to consider how the concepts and framings related to the local context of Glasgow, by exploring each concept (e.g., impacts, hazard, exposure, and adaptive capacity) in turn. A summary of activities is offered below.

#### *7.10.1.2* Identifying impacts and related hazards

The first session of the workshop explored climate impacts[43], or effects on natural and human systems of extreme weather and climate events. The participants were initially asked to consider impacts of heat events, either experienced or predicted, for Glasgow and record these on post-it notes. After fifteen minutes of brainstorming individually, the group was brought together to collectively discuss all the responses. Twenty-five different impacts were identified. These were clustered based on similarities and then

[43] Impacts refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system (IPCC, 2014).

two clusters were prioritised to explore in more detail (this decision was reached by consensus). The group then identified the climate hazards that caused the identified or predicted impacts. The purpose of this session was to help the group understand what hazard[44], as opposed to climate driver of heatwave, had led to the identified impacts (which included positive and negative examples). Based on the group discussion on hazards, two were identified as of interest for further exploration through the day's workshop. These included (i) overheating of buildings and (ii) changes to use and function of public space.

#### *7.10.1.3* Identifying exposure, sensitivity, and adaptive capacity variables

The participants were divided into two groups to explore each hazard separately. Each group was asked to explore influences on the specific hazard by addressing the following prompts:

i. Each group was asked to identify aspects which influence exposure[45] to the hazard they were exploring and record these on post-its.
ii. The groups were then asked to unpack the concept of sensitivity[46] in regard to each hazard. A number of factors affecting sensitivity, including physical or social characteristics which affect the likelihood that heatwaves will have a negative impact. For example, older people tend to be more susceptible to the effects of high temperatures or those with limited mobility or experiencing social isolation may not be able to seek help. Participants were asked to identify aspects which determine sensitivity and record these on post-its.

---

[44] Hazards were defined as "The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources." (IPCC2014, P.1766).

[45] The IPCC definition as "the presence of people, livelihoods, species or ecosystems, environmental functions, services and resources, infrastructure, or economic, social or cultural assets in places and settings that could be adversely affected" (IPCC 2014, p.1765) was presented to them.

46 The definition of sensitivity provided was, "The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change" (IPCC 2014).

iii. After discussion on the hazards and exposure, participants were asked to identify what factors affected adaptive capacity[47] and record these on post-its. Adaptive capacity in this context was proposed to include the ability to prepare (e.g. knowledge, technology, resources); ability to respond (e.g. income, personal mobility, building type, tenure, social networks, availability of public spaces, GP services) and the ability to recover (e.g. insurance, institutions, economy) (Hansen & Bi, 2017).

After identifying impacts, exposure, hazard, sensitivity and adaptive capacity, participants were provided with the framework and asked to draw initial relationships between variables. Workshop participants were asked to remove duplicates or any unnecessary variables and to review if anything is missing, if so, add it in. This produced two different system understandings of each hazard and the variables for the initial QPNs. A questionnaire was distributed at the end of the workshop with feedback requested on how participants found they process so far (available in Appendix XV).

### 7.10.2 Phase Two: identifying influences and synergies

Phase two focused on developing the network structure by reviewing and adding influences between variables as well as the inclusion of synergies between influences. This phase was informed by a second workshop held in February 2020 with the same stakeholders that attended the first workshop. Steps undertaken in the workshop included (i) validation and refinement of QPN structure and content and (ii) eliciting strength of influence and synergies. Qualitative questions were posed to stakeholders. Participants were asked:

(i) Which nodes are related to / influence each other?
(ii) Is it a positive or negative relationship?
(iii) How strong is the relationship? (Using a score from 0-7 with 0 being weak and 7 being very strong)

---

47 Adaptive capacity was introduced and defined as "The ability of systems, institutions, human and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences" (IPCC 2014).

The QPN was then annotated with numerical values that corresponded with the type and strength of influence stakeholders had indicated.

### 7.10.3 Phase Three – Options Analysis

Phase three focused on using the QPN to analyse potential adaptation options (as opposed to phase two which focused on developing the network to analyse the system as a whole). Phase three also used input from the second workshop in February 2020. Possible adaptation actions were proposed at both workshop one and two based on the content of the initial QPN. Actions were both on-going or needed. Each of these actions was discussed collectively in turn, in relation to how it would affect the developed network. For instance, stakeholders were asked:

(i) What variables (or nodes) in the network would this action influence?
(ii) What would the type and strength of the influence be?
(iii) What is the relationship between this action and other proposed actions? Would the outcomes be improved together? How strong is this relationship (synergy) (on a scale of 0-7)?

I annotated the responses onto the physical hard-copy QPN. This process used the collective system understanding of stakeholders to perform high-level appraisal of actions with stakeholders. Options appraisal was supported by the co-produced QPN which illustrated strength of influence of actions on variables in the network, identified key pathways to achieve the objective of resilience (to heatwaves) and noted synergies between undertaking actions together.

The QPN used with stakeholders and the decision-maker was not quantified due to limitations of the study (time availability and the COVID 19 pandemic resulting in stakeholders being furloughed) and thus methodological choice to use an adjusted QPN. As such, sensitivity analysis was also not undertaken. Following the in-person workshops which used hand-drawn networks, the resulting adjusted QPN was however, transferred to QGenie, which is “an interactive program that allows for rapid creation of causal models of uncertain domains” (Bayes Fusion LLC, 2020b). At this stage, I added probability information pertaining to parent nodes based on group discussion and available datasets, to explore the QPN myself in more detail.

Feedback on the process was sought at the end of each workshop during Phase One and Two. Evaluation was undertaken first through a verbal group conversation with notes being taken and secondly via a written questionnaire each time (questionnaires available in Appendix XV and XVI respectively). The verbal feedback session was held to receive comments on how participants found the process and then attendees recorded fuller responses on a questionnaire. The main questions posed during the oral feedback session at the workshop were:

- How difficult or easy was the process today?
- How useful is the resulting QPN?
- What would you like changed in the future?

The questionnaire used to assess the participatory development process was informed by the evaluation frameworks of Maskrey (2016) and Webler (2002). An important element of the questionnaire was seeking stakeholder feedback on how they found the process of developing the QPN and how useful the produced output was for their purposes. Levels of difficulty were rated on score of 1-5 using closed-ended questions. Questions were asked to evaluate practical criterion such as usefulness of the process. In addition, I undertook a semi-structured interview with the decision maker. They were asked:

- Do the results from the QPN help you identify appropriate adaptation actions?
- Do you understand the network and the outputs?
- What do you see as the advantages and limitations of this method to support climate adaptation decision-making?

The results from the QPN development process are presented in Chapter 9. A comparative assessment of the QPN process and outputs in relation to the BBN study is offered in Chapter 10 in relation to the CCP challenges identified in Chapter 6.

### 7.11 Data Analysis for Research Objective Two

The value of BBNs and QPNs to climate adaptation decision-making was assessed via combination of observation from developing the networks with stakeholders, feedback questionnaires and interviews with the GCC decision maker. The collation of these sources allowed me to develop a rich understanding of the perceived usefulness of these approaches within the research setting, in terms of addressing the challenges to decision-making identified in Chapter 6. Furthermore, analysis of these findings complemented and contextualised the learning and information I received from the methodology used to achieve research Objective One (as described in Chapter 5). The learning and feedback on the usefulness of BBNs and QPNs was analysed using the headings of context, content, and process, as described in Section 6.3 and presented in Section 10.1-10.3.

# Chapter 8: Exploring application of Bayesian Belief Network to support decision-making on pluvial flooding

> "Despite [that] Bayesian Networks are popular integrated modelling tools to deal with uncertain and complex domains, their application in the context of climate change still represent a limited explored field."
>
> (Sperotto et al., 2017, p.320)

In addressing Research Objective One, Chapter 6 outlined a range of challenges affecting climate adaptation decision-making. Firstly, it was identified that climate adaptation decision-making is influenced by the context in which it occurs, which in this study was defined by a lack of resources, time, and technical skills as well as a changing policy landscape. Secondly, the data and evidence (or content) used to inform decision-making was incomplete and not integrated within the options appraisal process. Thirdly, there was a lack of robust processes to identify, appraise and prioritise options. Findings also revealed that no assessment criteria or decision support methods were used to evaluate options.

Considering these findings, Chapters 8 and 9 explore decision support methods to address the challenges identified. A method identified that has not been applied very widely to climate adaptation to date, Bayesian Belief Networks (BBN), is studied in this chapter. The aim of this chapter therefore is to assess if BBNs are useful methods for climate change adaptation decision-making at the city-level. The different phases undertaken to develop the BBN included: (i) constructing the qualitative network; (ii) quantitative elicitation; and (iii) analysis. Further information on the detailed steps of the methodology is available in Section 7.3. Each phase will now be explored in turn, summarising the activities undertaken and reflecting on emerging findings.

The remainder of the chapter is structured as follows. Section 8.1 explains how the BBN was structured and the qualitative network developed, Section 8.2 presents the results of quantification of the BBN and Section 8.3 explains the analysis of the BBN. Then Section 8.4 discusses the benefits and limitations of BBN approach to climate adaptation identified, whilst Section 8.5 concludes the chapter.

## 8.1 Phase One: Constructing the qualitative network

The BBN created within this chapter explored pluvial flooding in Glasgow. Pluvial flooding is rain-related flooding occurring after a short intense downpour, where water cannot be evacuated quickly enough through drainage systems or infiltrated to the ground (Grahn & Nyberg, 2017; Houston et al., 2011). Pluvial flooding is a risk for Glasgow (Houston et al., 2011). Climate impacts coupled with socio-economic demographics, has resulted in Glasgow being identified as one of the ten most flood disadvantaged local authorities in the UK (Sayers et al., 2017). Pluvial flooding is also anticipated to increase in frequency, severity and impact in the future as a result of both climate change and increasing urbanisation (Rosenzweig et al., 2018).

Before the network is presented, a reflection on the approach undertaken is offered. When modelling problems, there is a need to consider the appropriate level of detail required (Brooks and Tobias 1996). This consists of a spectrum from the minimum basic model that conveys the problem (and that the decision maker can use), i.e. a requisite model through to an accurate and detailed depiction of the problem, a replicate model (Lin et al. 2008; Philips 1982). Lawrence D Phillips proposed the concept of requisite modelling in the 1980s. According to Phillips (1984) a requisite decision model is defined as “a model whose form and content are sufficient to solve a particular problem”. Features of requisite modelling include not incorporating content that doesn’t substantially improve the output of the model and approximating or simplifying complex relationships (Phillips, 1984).

Whether a model is requisite or not depends on the information available and the problem owner (Phillips, 1984). Such models are typically developed via interactive process with problem owners and specialists or decision analysts (Phillips, 1984). A requisite model reflects the shared understanding of the problem-by-problem owners.

The methodology and approach used within this thesis aligns with Phillips' proposal. As has been discussed, climate adaptation is inherently complex and cross cutting. As such, I engaged different experts to elicit values to populate different sections of the BBN that related to their respective areas of expertise. It was felt that no one expert would know everything relating to the problem domain being explored by the BBN and therefore different experts were required.

If this research were instead to take nodes and break them down into more granular level, this would result in more nodes and a significantly larger BBN. The more complex a BBN gets, often the more intractable it becomes. This research was cognisant of research context and used this insight to inform the methodology used. The decision maker was using the BBN to understand the situation and possible impacts of options, i.e. the effect of pulling levers. The decision maker was not using the precise quantification to inform specific decision-making, and therefore such specificity and precision was not required.

It is acknowledged and accepted that the BBN contained within this thesis is not 'perfect', however given the constraints and challenges of the research context and decision maker (as discussed in Chapter 6), it is believed to be sufficient to support the decision maker reach the decisions needed. The BBN sought to address the CCP challenges identified and thus be resource efficient, minimum elicitation burden and simple to understand. The BBN developed captured the important features of the problem and as such provided a framework or structure to understand the problem, in order to identify and appraise potential adaptation actions. This research setting was influenced by resource constraints. Given the very limited amount of time and human resources available, it is argued that for the time and effort devoted to the BBN development, it captured and quantified elements to the correct level of detail.

Phase One involved constructing the qualitative network of the BBN to explore pluvial flooding. The network was structured around an adapted IPCC AR5 framework of climate risk (as discussed in Section 7.3.1). Figure 8.1 shows the structure used to guide network development including components on: (i) exposure; (ii) adaptive capacity; and (iii) resilience of public sector institutions. Stakeholders identified main variables (nodes) and the links between them (directed arcs) for exposure, adaptive capacity, and resilience of public sector institutions, in relation to pluvial flooding. The result of this process was the creation of the qualitative network. The following section introduces each component of the network.

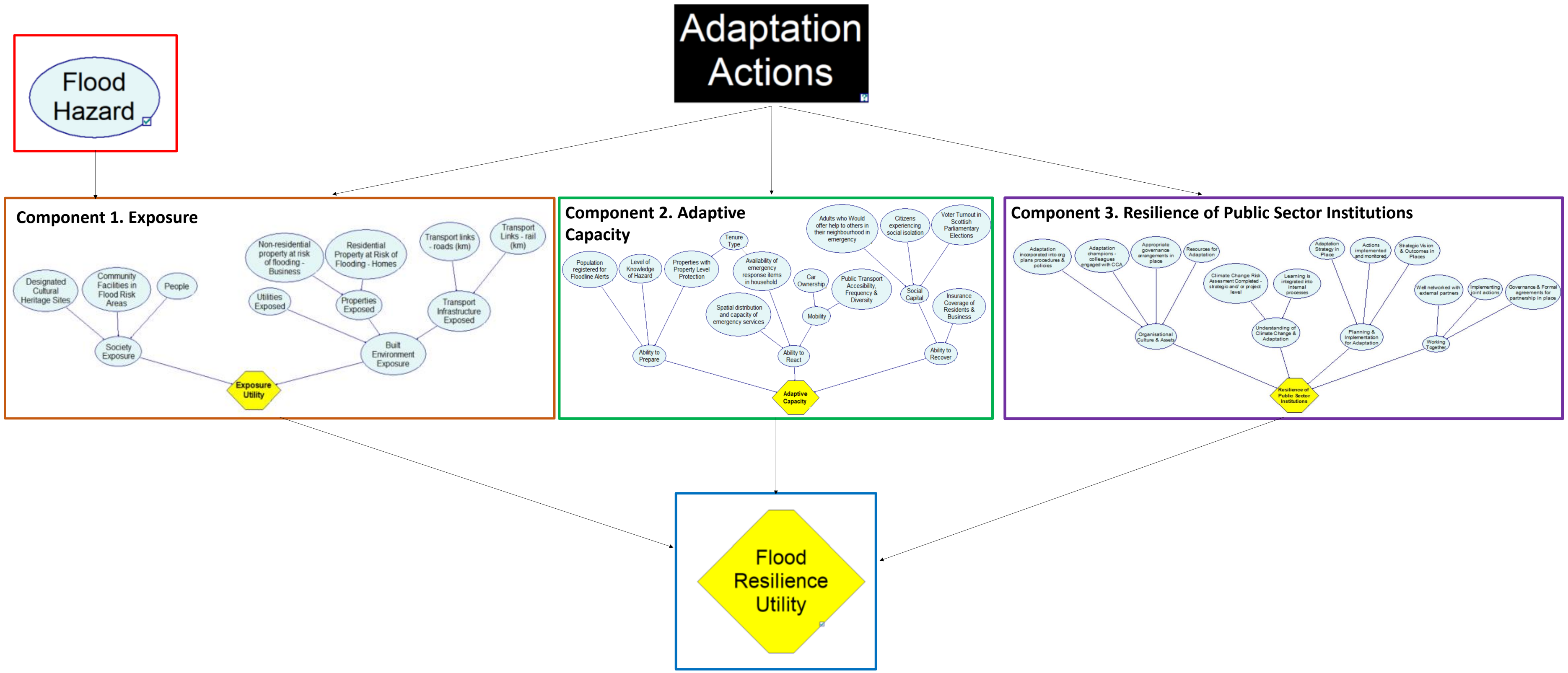
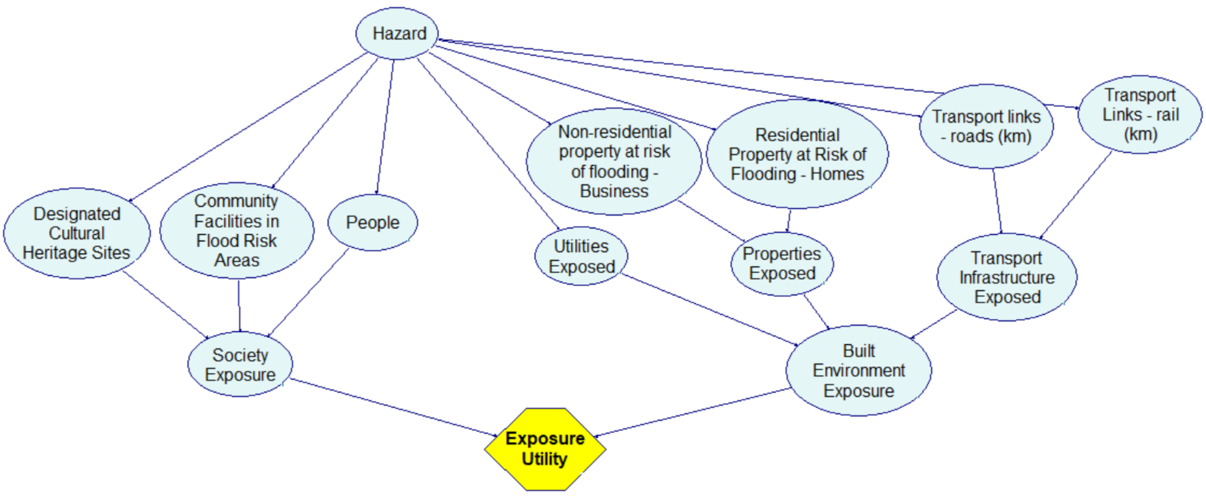



*Figure 8.1: Structure for BBN Development showing different components of 1. Exposure, 2. Adaptive Capacity and 3. Resilience of Public Sector Institutions. Each component was conditionally independent from each other however actions can affect all components of BBN. Numbering of components are used as reference within remainder of chapter.*

### 8.1.1 Component 1: Exposure

The exposure component of the BBN was divided into two sub-components: (i) built environment and (ii) society exposure. Exposure[48] refers to an area or location where a hazard may occur (Cardona et al., 2012). Variables relating to built environment exposure included transport exposure (including both road and rail), properties (both residential and non-residential) and utilities exposed. For societal exposure, the nodes identified included people, community facilities and cultural heritages sites at risk. Figure 8.2 presents the BBN exposure component structure. Variables relating to the natural environment were not identified or suggested by stakeholders and thus not included. Appendix XI summaries each variable within the exposure component of the BBN, by describing nodes, possible states and justification for inclusion in the BBN.

Quantification of the exposure component was undertaken using both publicly available data and expert elicitation. Pre-existing data on flood exposure for Glasgow was obtained from the Scottish Environmental Protection Agency (SEPA). This data was used to populate nodes on exposure of transport infrastructure, utilities, buildings (domestic and non-domestic), people, community buildings and cultural heritage. The remaining CPTs (of which data were not available) were populated via expert elicitation.




48 Exposure relates to the factors of an environment or context, which accentuate or offset the severity of climate events (floods and heatwaves). Exposure is a determinant of risk, but not solely by itself. A location or asset can be exposed but not vulnerable. For example, houses can be built in a floodplain which means they are exposed but may have adaptation measures in place to protect against floods meaning they have reduced vulnerability. Further information on the concept of exposure is available in Section 3.2.

*Figure 8.2: Image of the BBN Exposure component showing identified nodes and arcs (further described in Appendix XI). Blue nodes represent chance nodes and yellow colour represents utility nodes.*

The hazard node only influenced variables within the exposure component of the BBN. The hazard node contained four states representing different flood events. The states were based on the UK Met Office National Severe Weather Warning Service categories which assign flood events a colour depending on the impact the weather may have (Met Office, 2017):

- **Yellow Warning:** Flood will cause some low-level impacts, including some disruption to travel in a few places. Many people may be able to continue with their daily routine, but there will be some that will be directly impacted.
- **Amber Warning:** There is an increased likelihood of impacts from severe weather. This means there is the possibility of travel delays, road and rail closures, power cuts and the potential risk to life and property.
- **Red Warning:** Dangerous weather is expected. It is very likely that there will be a risk to life, with substantial disruption to travel, energy supplies and possibly widespread damage to property and infrastructure.

These states were selected for consideration as proxies for flood types. A no flood state was also included. The CPT for the hazard node was populated with local data on the likelihood of each type of flood event from SEPA (SEPA, 2015).

### 8.1.2 Component 2: Adaptive Capacity

Adaptive capacity is the ability of a social or environmental system to adapt to the impacts of climate change, as described in Section 3.1. Adaptive capacity is context specific and shaped by dynamic variables that differ in existence and influence amongst areas (Engle, 2011). As such, stakeholder feedback helped identify Glasgow relevant variables as well as dependences between said nodes.

The structure of the adaptive capacity component was divided into three subcomponents including (i) the ability to prepare; (ii) ability to respond; and (iii) ability to recover as suggested by Lindley et al. (2011) and agreed by the stakeholders consulted. The identified influences on the ability to prepare included tenure type, knowledge of hazard and registrations for Floodline (the Scottish flood warning service). Secondly, the identified nodes for ability to react included provision of emergency response items within households, distribution of emergency responders and mobility which was affected by private car ownership and public transport accessibility. Thirdly, ability to recover was suggested by the stakeholders, to be influenced by insurance coverage and social capital. A visualisation of this section of the BBN is offered in Figure 8.3. A description and justification of these nodes along with description of states is offered in Appendix XII.

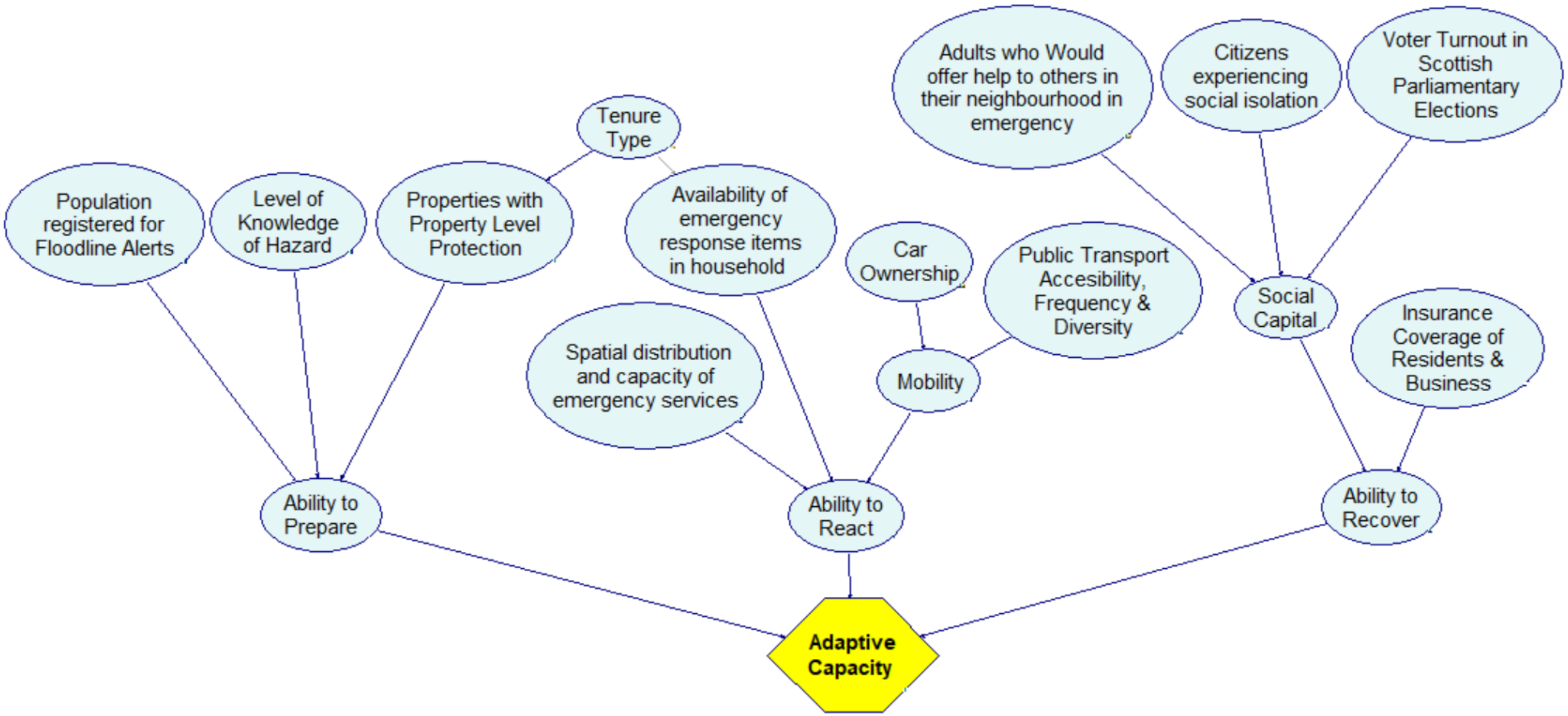



*Figure 8.3: Adaptive capacity component of BBN visualised*

### 8.1.3 Component 3: Resilience of Public Sector Institutions

When constructing the network structure with stakeholders, the theme of resilience of public sector institutions proposed within the framework was approved. No variables for this subcomponent, however, were suggested by stakeholders at the workshop. This may be because indicators based on the literature were available for other components but not this component. As such, this section of the network was both constructed and then later quantified with a single expert. The structure and content of this section of the BBN is based on Adaptation Scotland's Adaptation Capability Framework[49], a resource to support public bodies to adapt.

The Adaptation Capability Framework is premised on the idea of four adaptation capabilities that public sector organisations need to develop over four maturity stages. The BBN component, resilience of public sector institutions, offers a simplified version of this framework. The framework was chosen to guide BBN development, as GCC were familiar with the emerging framework and the terminology used in it. Four subcomponents were identified including: (i) Organisational Culture & Assets; (ii) Understanding the Challenge of climate change and climate adaptation; (iii) Planning & Implementation of adaptation; and (iv) Working Together. The nodes within this network component are visualised in Figure 8.4 and justification for their inclusion within the BBN is described in Appendix XIII.

[49] The Adaptation Capability Framework (ACF) was released in 2019 and became the guidance for all public bodies in Scotland on how to adapt, replacing the former '5 Steps to Manage Climate Risks' discussed in Chapter 3 Section 1. It also won the IEMA Climate Resilience Award in 2020. I co-created the ACF and was second author on the published Handbook. I also continued to support GCC in using the Framework following PhD research engagement through my role as an adaptation practitioner.

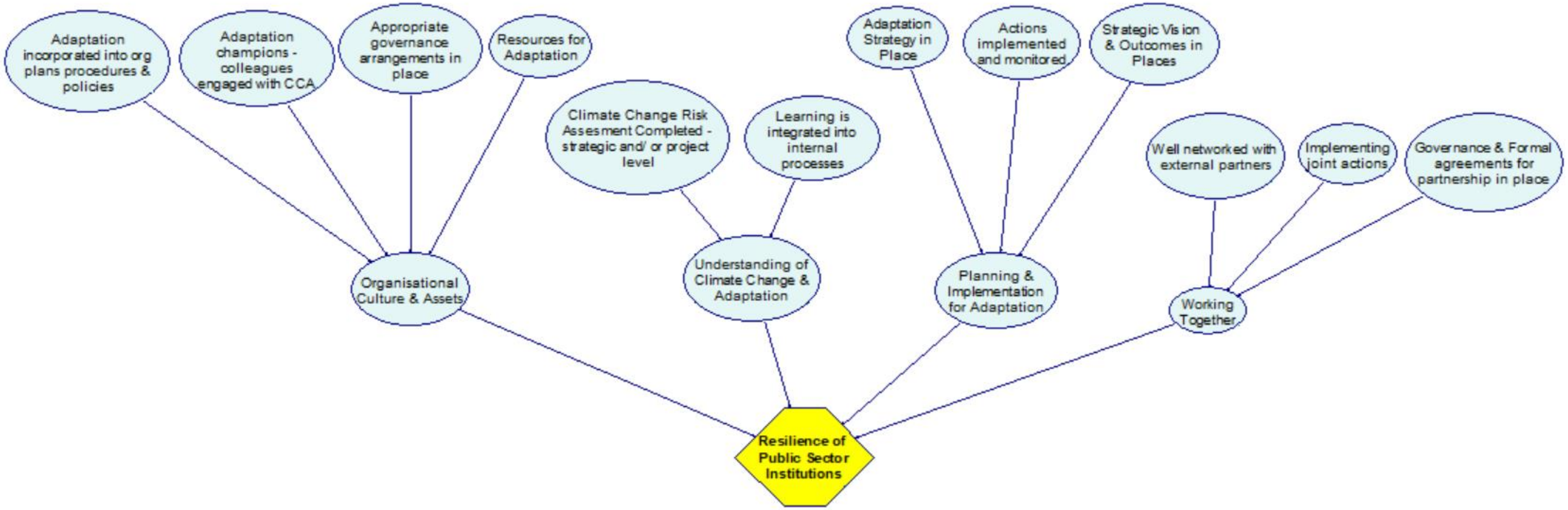



*Figure 8.4: Resilience of Public Sector Institutions BBN Component*

### 8.1.4 Constructing qualitative network structure

The previous sections have described the three different components of the BBN, including: (i) exposure; (ii) adaptive capacity; and (iii) resilience of public sector institutions. As was discussed in Section 8.1, these three components combine to comprise the flood resilience BBN. Climate resilience is not directly observable so must be inferred from measurements of observable attributes or indicators. A common element of existing frameworks is that resilience is broken down into multiple components and made to be relevant through inclusion of local data or expert elicitation (Clare et al., 2017), as was the case in this research.

Other academics have also treated the concepts that influence risk and resilience, discretely for the purpose of modelling. For example, Yu et al. (2021) created hazard and category specific vulnerability indices based on exposure, adaptive capacity and sensitivity sub-scores which were then combined to explore climate change-related health hazards spatially. Lindley et al. (2011) also examine adaptive capacity (comprised of ability to prepare, react, and recover), along with sensitivity and exposure separately to later produce a socio-spatial index of climate disadvantage to highlight extremes in climate-related social vulnerability in the UK. Lastly, Richards et al. (2013) whilst not using the concepts or terms of exposure and adaptive capacity, did structure a BBN around distinct components relating to the ability to prepare, prevent, respond and recover.

The subsections of exposure, adaptive capacity and public sector resilience collectively represented the BBN for flood resilience. Each component of the BBN fed into a utility node. The BBN was structured in this way for simplification. The components were treated independently in order to simplify the network and make it more accessible to stakeholders constructing the network and experts eliciting values. The components were then brought together into an overarching BBN by the creation of a flood resilience utility node, which will become the focal point of subsequent analysis. Multi-criteria utility analysis is thus being undertaken. The descriptions of each utility node are summarised in Table 8.1. The flood resilience utility was calculated as:

Flood Resilience Utility = Adaptive Capacity Utility + Resilience of Public Sector Institutions Utility + Exposure Utility

Table 8.1 describes the different utility nodes within the BBN that combine within the above equation.

*Table 8.1: Summary of Utility Nodes in BBN*

| **Utility Node** | **Description** |
|---|---|
| Adaptive Capacity | A utility score of 0 is where there is no adaptive capacity, so there is no ability to prepare, react or recover amongst citizens in Glasgow, whilst a score of 100 represents extremely good adaptive capacity with access to information, flood alerts, emergency services, support amongst communities and insurance resources available following a flood event. |
| Resilience of Public Sector Institutions | A utility score of 0 is where there is no maturity of public bodies across the four identified adaptation capabilities of organisational culture and assets, understanding of climate adaptation, planning and implementation of adaptation and working together, whereas a 100 represents advanced maturity and resilience of all public bodies across all four of the capabilities. |
| Exposure | A utility value of 0 means that everything is exposed (across society and built environment), whereas a utility value of 100 implies nothing is exposed. |
| Flood Resilience | The flood resilience utility is calculated by summing adaptive capacity, resilience of public sector institutions (both positive attributes) and exposure. A flood resilience utility value of 0 means that there is no resilience present, whereas a value of 300 represents a very robust, resilient city (in relation to pluvial floods). |

As the formula illustrates, all components of the BBN were weighted equally. This is due to the feedback from the decision maker at GCC. When I asked them if any of the components should have greater weighting in the overall flood resilience utility estimates, she replied that she did not have enough insight or information to justify such changes and she requested to keep all weightings the same. This is line with the approach used by Lindley et al. (2011) in the Joseph Rowntree Foundation report, ‘Climate change, justice and vulnerability’ and the Scottish Government Flood Disadvantage Report (Scottish Government, 2015). The authors stated this was because of “insufficient understanding of the relative importance of dimensions of social vulnerability for determining uneven outcomes” (Lindley et al. 2011, p.107). Their research explored alternative weighting schemes with Scottish stakeholders but found a lack of any consensus. This highlights the (still outstanding) need for research on how dimensions of climate resilience should be weighted, preferably in consultation with affected communities directly.

The assumption of equal weighting is contestable. However, in the case of this study it was a result of the research setting and decision-maker requests. In relation to the BBN, equal weighting can evidently obfuscate differences at the sub-component level (such as exposure, adaptive capacity) by presenting the same overall utility value. For example, Table 8.2 shows two hypothetical situations. In situation A, there has been a decision to focus on economic development, with expansion of housing, private development and transport in flood prone areas with no physical climate resilience considerations or measures. Commitment and action to individual and institutional climate resilience however does appear. This would result in an exposure, utility value of 0, and utility values of 100 for adaptive capacity and resilience of public sector institutions, resulting in overall flood resilience utility of 200. In situation B, there is a strong focus on public sector climate adaptation with mandatory climate literacy training, adaptation budgeting and reporting occurring, making the resilience of public sector institutions utility value 100. Exposure and adaptive capacity remain unchanged at a utility of 50, resulting in an overall flood resilience utility value also of 200. These hypothetical situations are provided to explain the relationship between utility scores in the BBN and the need for analysis at both levels. As such, the effect of adaptation interventions is considered at the component and overall flood resilience utility value level to interrogate how the adaptation actions would affect the system.

*Table 8.2: Example of how different situations may result in same overall flood resilience utility value but different utility values at the BBN subcomponent level*

| | Situation A | Situation B |
|---|---|---|
| **Adaptive Capacity Utility** | 100 | 50 |
| **Resilience of Public Sector institutions Utility** | 100 | 100 |
| **Exposure Utility** | 0 | 50 |
| **Flood Resilience Utility** | 200 | 200 |

The decision to use equal weighting was a pragmatic choice, based on the decision makers confidence and competence in specifying weighting. The decision maker did not allow me to explore these further. This limitation is recognised. Future research should explore how altering these weightings would affect outcomes and decision-making and the practical challenges associated with determining them for city-level adaptation decision-making.

## 8.2 Phase Two: Quantification of BBN

Following the qualitative network development, the conditional relationships between variables were quantified. BBN parametrisation involves assigning states to each variable and computing conditional probabilities representing the strength of relationships between variables (Sperotto et al., 2017). States and probabilities were assigned to each variable in the network using existing data and elicitation from experts and were captured within the CPTs.

Before eliciting values from experts, a probability exercise was conducted (Appendix VIII). The results of this exercise varied amongst experts consulted. Two of the three experts comprehended probabilities as evidenced by getting all the questions correct. One expert, however, got every single probability training question wrong. This resulted in additional training support offered to this expert before continuing with the elicitation process. This finding demonstrates the range in familiarity or use of probabilities in everyday practice. Experts then assigned percentages that represented their belief in the strength of the causal relationships between parent nodes and their child nodes (an example template is available in Appendix IX).

For effective elicitation, participants need to have expertise in the field and be able to understand or learn how to assess probability (Renooij, 2001). Other studies note that it can be difficult to find experts who are able to provide knowledge in appropriate format or ways which can be converted into probability distributions (Uusitalo, 2007). Although all steps were taken to ensure the appropriate expert was present and providing appropriate information, I was more interested in the intrinsic value associated with the development of the BBN than the accuracy of elicited data. As such, this was not a primary area of focus. I trusted the insight of experts because of their careers and experience. The resulting BBN is a ‘proof of concept’ attempt to explore the use of BBNs in supporting climate adaptation decision-making.

In addition to eliciting likelihood values to populate CPTs, utility values were also elicited. Utilities nodes explicitly represent the value of an outcome or decision within the BBN given each possible outcome state. According to Pollino & Henderson (2010, p.19) “the conditional table for a utility node describes the relevant expected cost or benefit for every possible combination of input states." Utility nodes contain a table of utility values, with one for each combination of parents for that node. These values demonstrate how each of the possible worlds represented by the parents are valued. Experts were asked to make judgements on utility values of variables within the different BBN component section. Each BBN subsection and thus each expert's CPT values were weighted equally. The resulting quantified BBN is illustrated in Figure 8.5.

The BBN was not elicited entirely by one person due to the belief that this would oversimplify it. The approach adopted in this study is pragmatic, acknowledging that the resulting BBN is not at a very detailed level nor too high an abstraction. There was significant potential for the BBN to become incredibly complex. This was purposefully addressed via the research design by quantifying the different components of the BBN individually with experts and then combining them. Integrating the BBN from the start would substantially increase the complexity of the process.

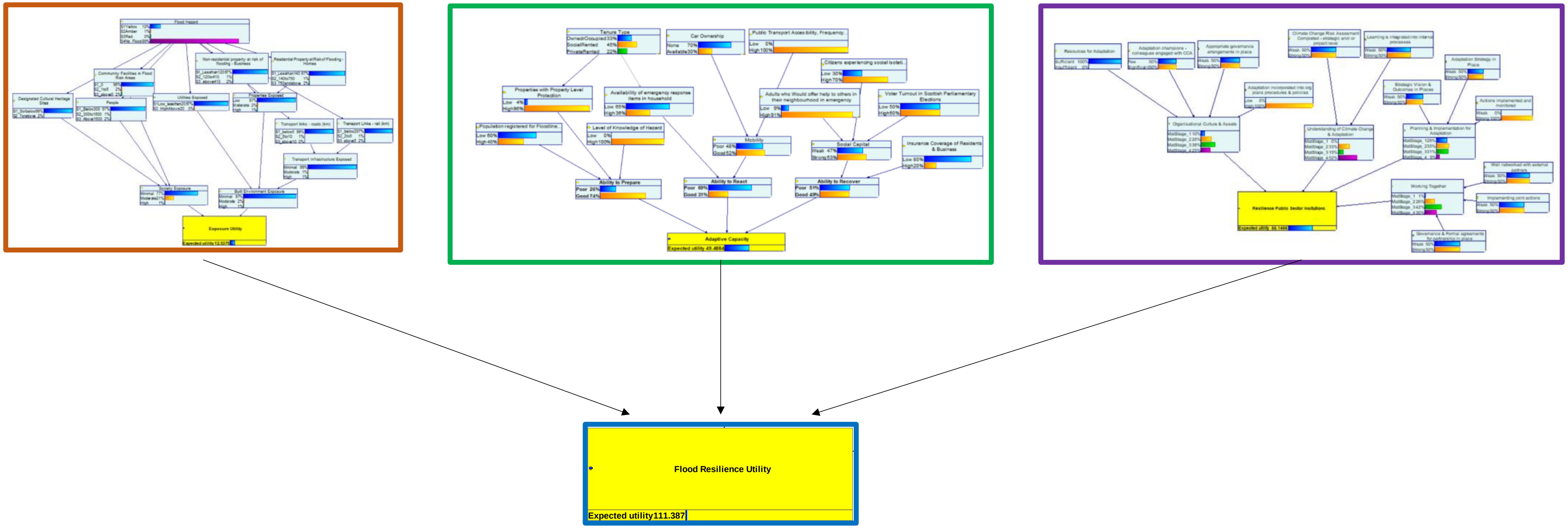



*Figure 8.5: Illustration of quantified BBN*

Phase Three: Analysis

Following the quantification phase, the third phase was analysis. The BBN was used to appraise identified adaptation options and sensitivity analysis was undertaken. Findings from each process are described in the remainder of this section.

### 8.2.1 Analysis of adaptation options using BBN

After quantification, the next step was using the network to explore the effect of different adaptation actions. The BBN was used to appraise pre-identified options, rather than identify potential options. This was because interventions to address pluvial flooding had already been identified in the Glasgow Adaptation Strategy and Action Plan development process (as described in Section 6.1). Analysis of the BBN was centred around addressing the following question: What is the impact of (alternative) adaptation actions on enhancing flood resilience? Five adaptation options were selected to be assessed using the BBN in Genie. The decision maker provided estimates of how each option would affect the nodes in the network and offered insight into why specific nodes would be affected. Figure 8.6 visually shows the influence of different options on nodes within the network. Table 8.3 provides a description of the five actions and identifies which nodes each action would affect.

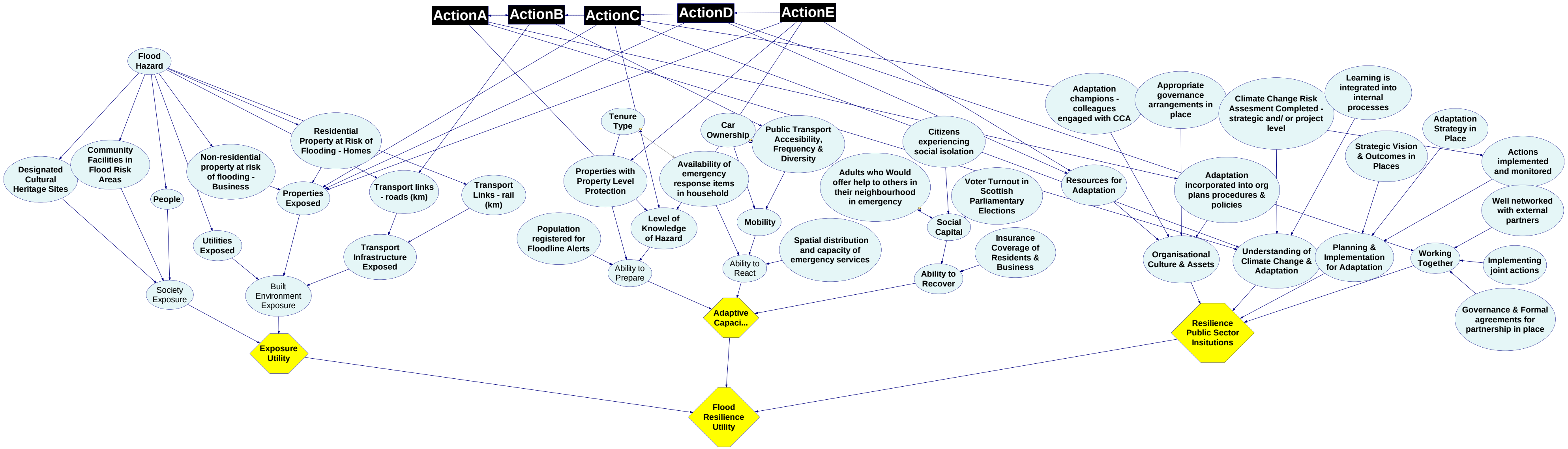



*Figure 8.6: Illustration of BBN at end of Phase 3 showing which nodes each adaptation action option influenced*

*Table 8.3: Description of five adaptation options assessed and identification of nodes in the network each action would influence*

| Adaptation Action Options | Description of Action | Nodes in BBN it would affect |
|---|---|---|
| **A Public Survey – on flood and resilience measure awareness** Survey of awareness of flood and resilience challenges and how to reduce impact / risk. | GCC proposed to ask the public what their perception of the risks of flooding are and what can be done to reduce risks of it occurring, rather than just react when it does happen. This action aims to raise awareness of the challenges of flooding and also what can and should be done to reduce the risks and impacts (by council and citizens) | -Level of knowledge of hazard (AC)<br>-Understanding of climate change adaptation (Res PI)<br>-Adaptation incorporated into plans, policies and procedures (Res PI) |
| **B Planning** Climate Resilient Transport Systems | NHS Greater Glasgow and Clyde (GGC) to work with GCC to influence climate resilient public transport to hospitals – ensuring buses are able to access hospitals frequently and that there are redundancies in the route and key transport links to hospitals priorities in response. | -Public transport accessibility, frequency, and diversity (AC)<br>-Transport links roads (Exp) |
| **C Capacity Building -** Awareness Raising on SUDS | Capacity building across the city to ensure wider understanding of the purpose and importance of sustainable urban drainage systems (SUDS) and other climate adaptation measures. Ensuring that designs of built environment account for projected changes in climate and weather patterns. Training to be prepared and rolled out across the city. | -Level of knowledge of hazard (AC)<br>-Understanding of climate change adaptation (Res PI)<br>-Property exposure (Exp)<br>-Actions planned and implemented (Res PI) |
| **D Policy** Influencing city deal projects to specifically include climate adaptation measures | This action aimed to work alongside city deal team and Central Scotland Green Network to develop an integrated plan for climate change adaptation solutions in the smart city centre district, deployment of a set of standard construction solutions that tackle adaptation within a street landscape design. The aim is to produce a unified strategy for adaptation deployment across university facilities, a toolkit that others can adapt, and a testbed for solutions and monitoring of their success. | -Resources for Adaptation (Res Pi)<br>-Working Together (Res Pi)<br>-Property exposure (Exp) |
| **E Retrofit** Working with residents and business to deliver retrofit surface water management interventions | Residents and businesses buy-in to delivering retrofit surface water management interventions on their land. This action aims to reduce the risk of flooding, improve water quality, enable sustainable development/regeneration, delivery of multi-functional blue green infrastructure, combat urban heat risks, improve air quality, create a sense of belonging/ participation, foster bottom-up communication and encourage community actions. | -Property exposure (Exp)<br>-Property level protection (AC)<br>-Level of knowledge of hazard (AC)<br>-Resources for adaptation (Res Pi) |

The BBN was used to assess the effect of each adaptation option and combinations of options implemented together, in relation to the calculated ‘Flood Resilience Utility’ value, and underlying utility nodes (of exposure, adaptive capacity and resilience of public sector institutions). Results were based on estimates provided by the decision maker. The questions posed to the decision maker to appraise options and seek feedback on the BBN approach are available in Appendix XVII. The expected utility of combinations of different decisions was also explored to consider the effect of multiple options occurring in tandem. These decisions or actions were considered within the present-day timeframe. Figure 8.7 illustrates the expected utility values of the flood resilience node with different permutations of options. Figures 8.8 then shows the effect of actions on exposure, adaptive capacity, and resilience of public sector institution nodes utility values. Both Figures 8.7 and 8.8 present data that a normalisation method (min-max scaling) has been applied to. The min-max method rescales data into a new range based on the following equation (Aksu et al., 2019):

$$X_{scaled=}\frac{x-\min(x)}{\max(x)-\min(x)}$$

Normalisation converts values into a common scale to support rating and ranking of alternatives (Vafaei et al., 2018). This was undertaken to enable the data to be compared used a common scale (0-100) without distorting differences in the range of values. To note, a value of 0 does not indicate that the action does not add value, instead it indicates that it is the ‘worst’ option of all the considered options.

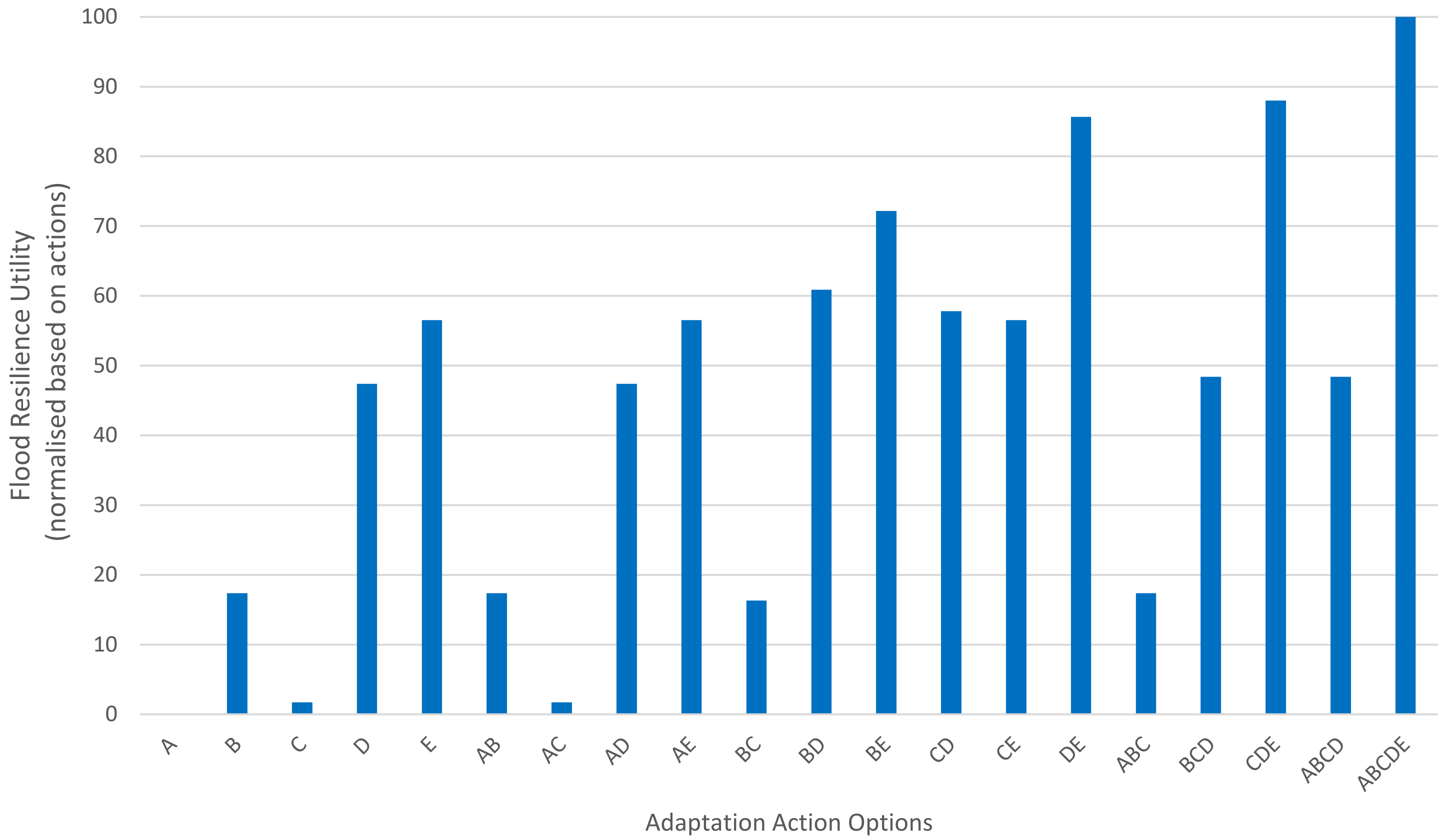



*Figure 8.7: Graph assessing how actions contribute to flood resilient utility. The data were normalised between 0 and 100 for adaptation actions to aid assessment*

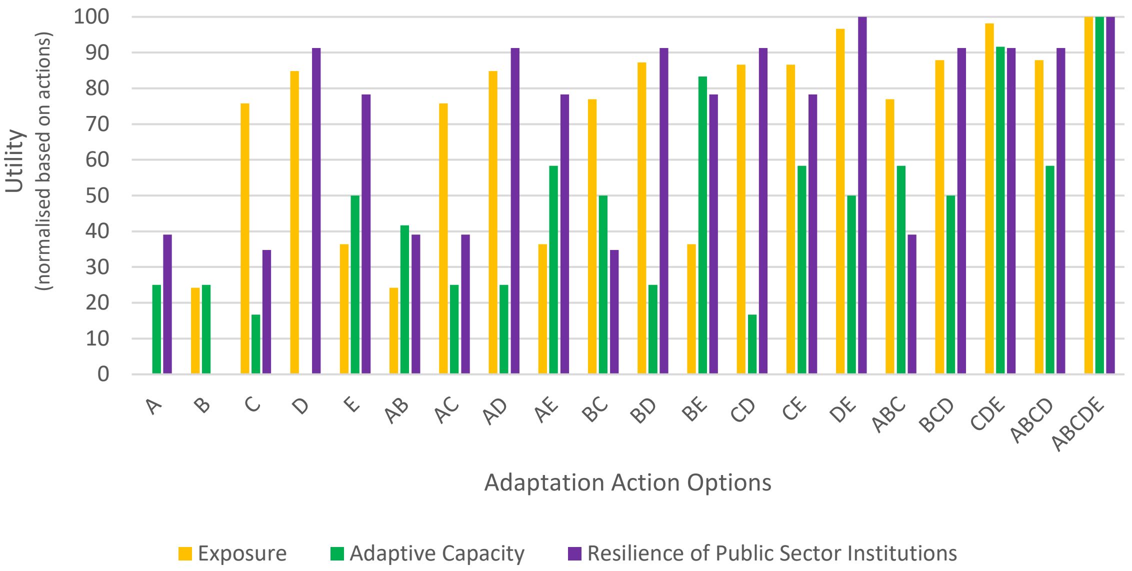



*Figure 8.8: Graph illustrating the effect of adaptation actions on the utility of BBN components (exposure, adaptive capacity, and resilience of public sector institutions) separately to show the varying benefits each action has across these components. Data were normalised between 0 and 100 for the best and worst action.*

The results illustrate the varying potential effects of each adaptation option on enhancing flood resilience utility (Figure 8.7). Analysis indicates that Option E, a work programme to deliver retrofit surface water management interventions, may enhance flood resilience the most. This may be due to the fact that this option influences four of the nodes in the BBN highlighting the co-benefits associated with the action. Similarly, the other actions which were seen to improve flood resilience the most (after Option E) include Option C which also has multiple benefits. It should be noted that Option A performs the least well, however it does have benefits. As the data has been normalised on the range of actions and A is the worst action that is why it appears to not have any impact in Figure 8.7, but Figure 8.8 shows the effect on subcomponents of the BBN. The reason for these results is because Options D and E involve taking adaptation action on the ground, which reduces exposure, builds adaptive capacity, and enhances resilience of public sector institutions, thus affecting multiple nodes in the BBN. Option C whilst it is more focused on capacity building, also influences many nodes across each of the components of the network. Options A and B on the other hand affect fewer nodes and to a lesser extent.

In addition to considering the potential impact of adaptation actions individually, the BBN supports the exploration of actions implemented together. Figures 8.7 and 8.8 illustrate a range of pairing and grouping of actions. Analysis indicates that Options D and E are the strongest performing actions individually and have an even greater impact when combined together (utility of 88). Similarly undertaking both Options B and E achieves a utility of over 70. Both figures illustrate that undertaking all actions is predicted to achieve the highest utility value (100), however the data also shows that just doing Options C, D and E achieves a utility value of 85. This information could hypothetically support a decision-maker in prioritising options, particularly if resources are constrained.

Figure 8.8 illustrates how the actions effect the components of exposure, adaptive capacity, and resilience of public sector institutions directly (which together comprise flood resilience utility). Three of the five actions were believed to affect the ‘level of knowledge of hazard’ node, which contributes to adaptive capacity utility (Figure 8.8). A focus on this area may be appropriate given that the city is still at the start of its adaptation journey and thus awareness raising, and education is critical to build base understanding. Adaptation responses must also consider influences on public perception of climate hazards. Perception of flood risk is highly contextual depending on previous flood experience as well as socioeconomic and demographic characteristics (Bradford et al., 2012). An example from practice comes from 2007 summer floods in England. At the time, the Environment Agency provided flood alert warnings, however the Pitt Review (Pitt, 2008) found that the warnings were not provided in easily understandable formats and did not provide clear explanation of action and thus were not acted upon. Communities with low levels of understanding to interpret flood warning or migrant communities who may also face language barriers may reduce adaptive capacity (Keogh, Apan, Mushtaq, King, & Thomas, 2011). The BBN enabled the exploration of the effect of improving adaptive capacity as a result of different options by focusing on the adaptive capacity utility values (Figure 8.8).

Two of the five actions were suggested to influence ‘resources for adaptation’ and thus organisational culture and assets, which was part of the resilience of public sector institutions section of the BBN. This highlights the need to address resource challenges, as explored in Section 6.4.1. Austerity has resulted in drastic cuts to public finance, whilst climate change has caused increasing costs associated with dealing with impacts and planning for the future. For instance, Lorenz et al. (2019) studied UK adaptation actors and found a dominance of public sector involvement (adaptation roles were two times more likely to be assigned to public than private) but questioned the capacity of such organisations to fulfil the allocated responsibilities given current resource commitments. The BBN indicates the influence on sufficient resourcing in enabling flood resilience. Assessment of how each of the adaptation actions affected resilience of public sector institutions is shown in Figure 8.8.

The options assessment focused on the effect of actions in the present day. Climate change, however, is likely to exacerbate the frequency and severity of flooding in Scotland. The UK Climate Projections 2018 data indicates an increase in winter precipitation (although this will depend on geographical region), intensity of rainfall to increase, more heavy rainfall events and an increased risk of surface water flooding in Scotland (Adaptation Scotland, 2021). As such, the Scottish Environmental Protection Agency (SEPA) released guidance on a ‘climate change allowance’ in 2019. The allowance for surface water flooding is based on peak rainfall intenstity and the total potential change for 2100 peak rainfall intensity is 55% in the West of Scotland (SEPA, 2019). Figure 8.9 shows analysis of how different adaptation actions would perform given different flood scenarios, including current likelihoods, climate change projects and the occurrence of a yellow, amber and red flood. This graph shows percentage change in flood resilience utility, in comparison to a baseline of doing nothing. Figure 8.9 thus illustrates the positive relationship between utility of actions increasing as the severity of flood event increases. For instance, the biggest increase in flood resilience utility, between doing nothing and taking adaptation actions, is when a ‘red flood’ occurs.

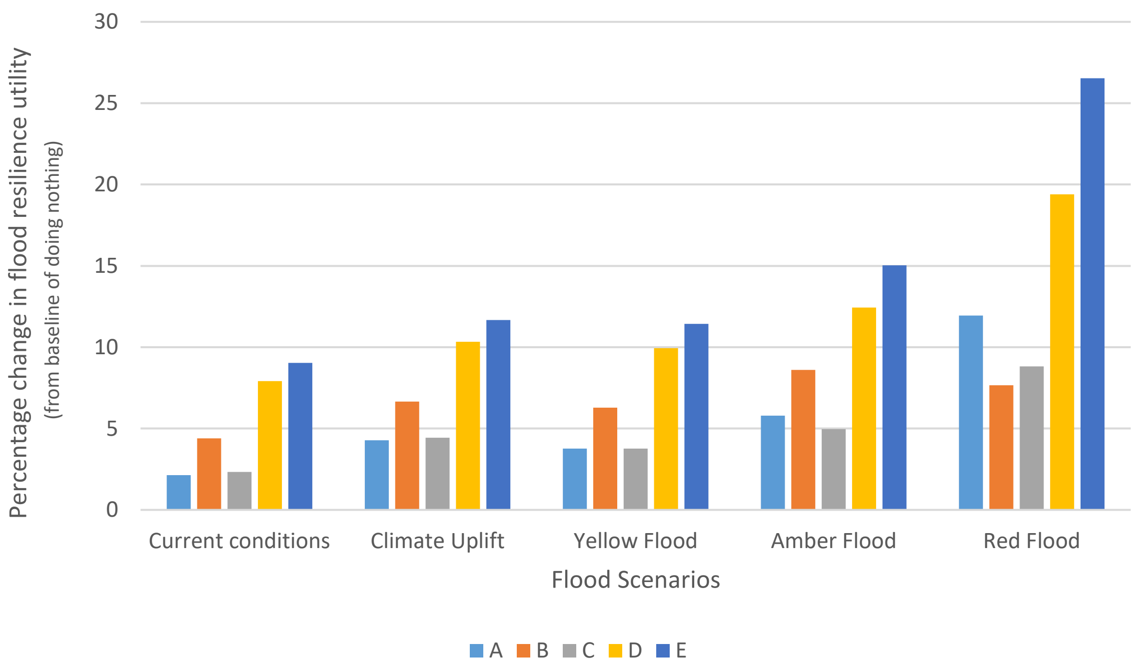



*Figure 8.9: Graph showing percentage change in flood resilience utility of each adaptation action given different flood scenarios. This demonstrates that utility generally increases as the severity of the flood incident increases.*

In addition, the BBN was used a prompt to consider different futures in a more holistic sense. The climate research community has developed Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) which provide future climate scenarios of future climate and social and economic conditions (IPCC, 2014b; Nakicenovic, 2000). Such international scenarios are now increasingly being scaled and adapted to different geographical and sectoral applications. In the UK a set of multi-driver qualitative and quantitative UK-SSPs has been developed via a participatory process with stakeholders (Pedde et al., 2021). The UK-SSP project describes shared socioeconomic pathways for the UK to support decision-making on climate resilience. Figure 8.10 summarises the 5 SSPs that were produced for the UK.

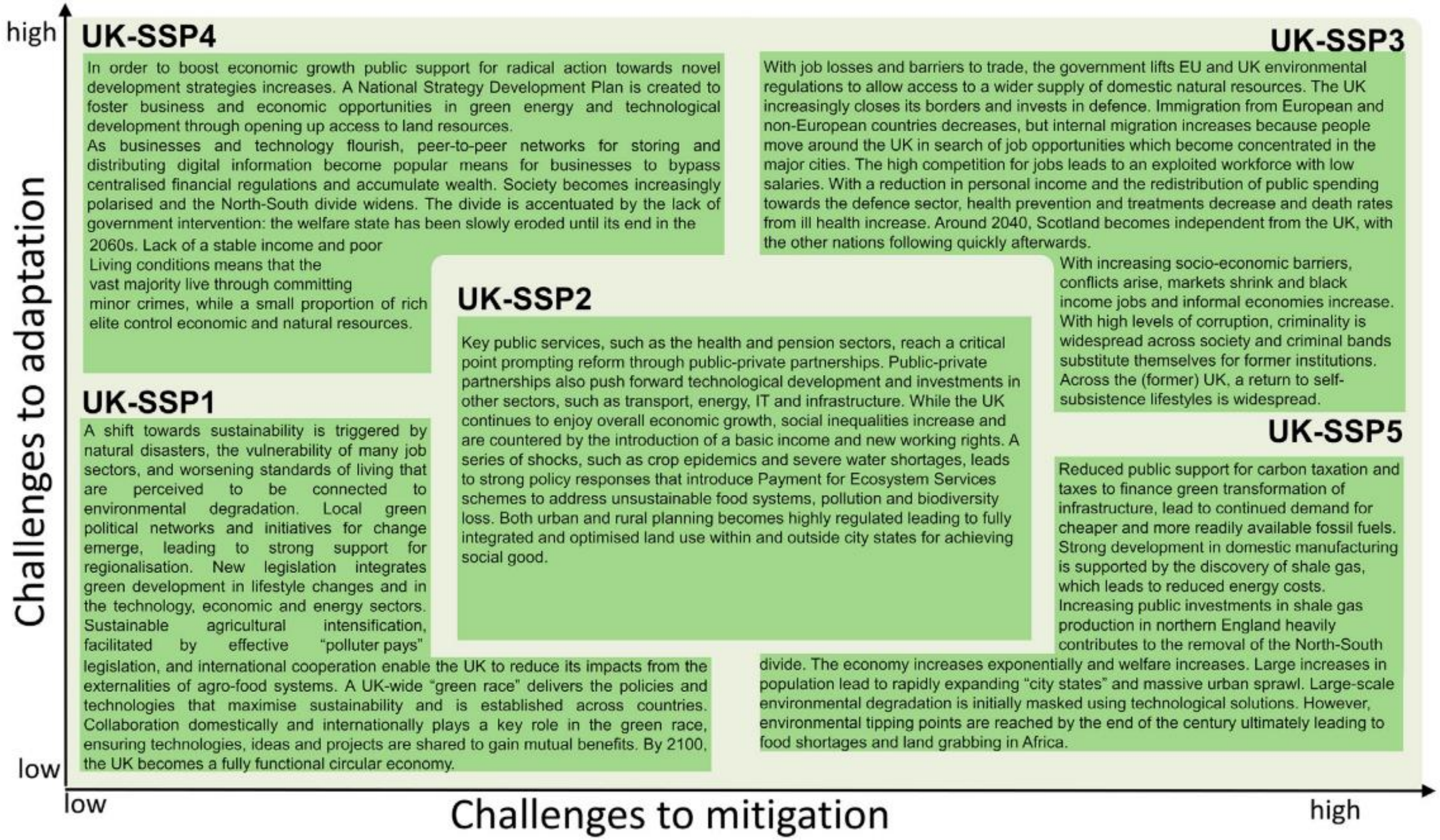



*Figure 8.10: Summaries of the UK SSP Narratives. Source:*(Pedde et al., 2021)

As shown in Figure 8.10, UK-SSP1 and UK-SSP4 are either ends of a spectrum of adaptation challenges. Given that these SSPs presented different consequences for adaptation, each was considered within the BBN. Figure 8.11 shows how the identified adaptation options contribute to utility values under each scenario through ‘what-if’ testing. These are based on the contents of the SSP summaries, as opposed to stakeholder consultation. For instance, UK-SSP1 represents an egalitarian future, with high public perception and awareness of climate change, an engaged and commitment government, and leaders, enhanced societal collaboration and empowerment. As such, nodes in the BBN that were affected (positively) include adaptation champions, integrated learning, strategic vision, governance, implementing actions, population registered for Floodline, availability of emergency items, properties with property level, adults willing to offer help, emergency services availability and social capital. Conversely, UK-SSP4 is defined by inequality and uneven development. As such, the nodes such a future would affect (negatively) in the BBN include transport exposure, social capital, willingness to help neighbours, and all of the nodes pertaining to the resilience of public sector institutions would be in their negative state.

The analysis of the percentage change in flood resilience caused by different options under each future is presented in Figure 8.11. This demonstrates that in an SSP4 future, while all the actions have increased value, there is a significant increase for Actions D and E when compared to SSP1. For both A and C, there is a significant increase from SSP1 to SSP4, however, these actions lag behind the other actions, which have even greater increases in utility. Figure 8.11 also shows us that in an SSP1 world, the percentage increase in flood resilience utility of these actions is relatively small (approximately 5%), however under an SSP4 world, the impact of actions is greater (at around 25%). This significant difference indicates the different contexts and thus consequences of decision-making. The data essentially shows that getting decisions ‘right’ when things are ‘good’ (SSP1) is not that hard, but not making the ‘right’ decision when things are ‘bad’ (SSP4) could have significant impacts (and associated costs). The BBN thus helps consideration of these different situations and which actions may be most appropriate given changing contexts.

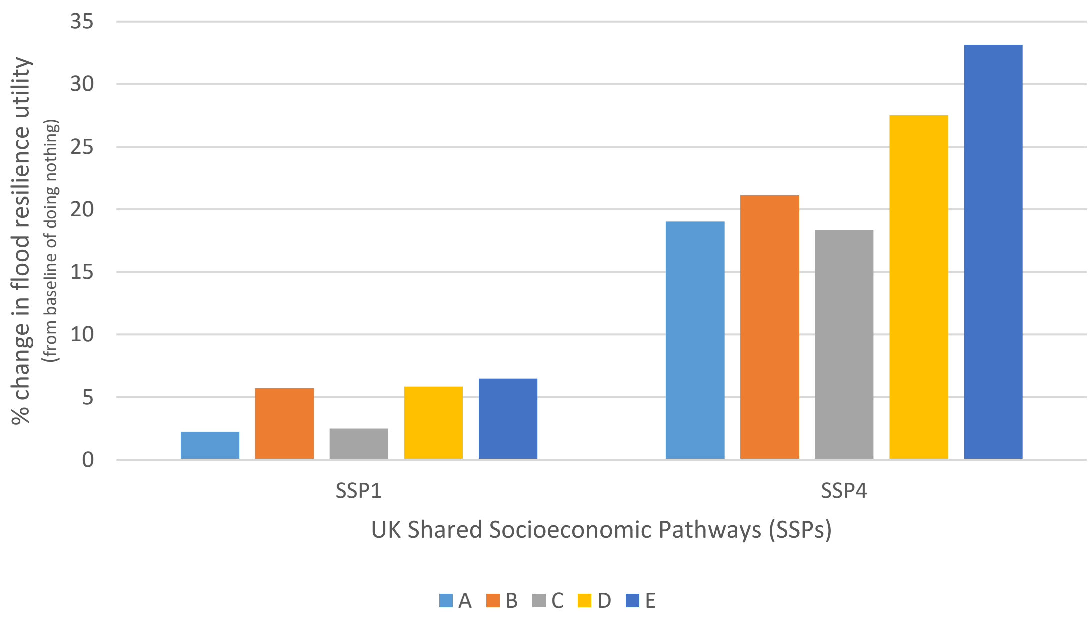



*Figure 8.11: Graph showing effect of adaptation actions on flood resilience utility under different UKSSPs*

In addition to a light touch options appraisal, Phase Three undertook sensitivity analysis of the BBN. Findings indicated which nodes were most sensitive as well as which adaptation options may enhance flood resilience the most. The next section summarises resulting findings.

### 8.2.2 Sensitivity analysis to identify significant influences on flood resilience

Sensitivity analysis was used to evaluate the relative influence on every variable in the network in relation to focus variables, in this case the utility nodes (Sanò et al., 2013). The sensitivity analysis was undertaken using an empirical approach where input parameters (probabilities of states of nodes) were modified one by one and subsequent changes in output parameters (e.g. posterior probabilities) observed and recorded as was done by Coupé et al., (1999). Sensitivity analysis can show causal pathways between variables which can help identify which variables may be best addressed by risk management or adaptation to reduce probability of undesired events or take advantage of any opportunity (Sperotto et al., 2017). Identifying sensitiveparameters can also highlight where more effort should be invested to improve results of BBN.

The results of the sensitivity analysis for exposure were (in decreasing order): (i) people; (ii) community facilities in flood risk areas; (iii) residential properties; (iv.) non-residential properties; (v.) utilities; (vi.) transport-roads; and (vii) transport-rail. For adaptive capacity, the top five nodes that were identified through sensitivity analysis as being highly sensitive were (in decreasing order): (i) insurance coverage; (ii) capacity and spread of emergency services; (iii) voter turnout; (iv) percentage properties with property level protection; and (v) population registered for flood line alerts.

Whilst this section summarised initial findings of how the BBN could support options appraisal, it is stressed that the BBN is not suggested as a replacement for the hydraulic, hydrological, economic or social models that would also be needed to support comprehensive adaptation options appraisal (Sayers & Meadowcroft, 2005). It is acknowledged that this options appraisal is rudimentary. Assessment is based on utility values, calculated as a result of exposure, adaptive capacity and resilience of public sector institutions. Costs associated with each option are not included in the BBN. This was a purposeful choice given that the decision-maker wanted to focus on the benefits of each possible option, without thinking of financial costs. In addition, estimated costs for each action were not available. This assessment is therefore more focused on initial prioritisation of options and could later be complemented by a subsequent cost benefit analysis (CBA). This study provided a 'proof of concept' BBN to assess how BBNs may support adaptation decision-making.

## 8.3 Discussion: Value of BBNs to climate adaptation decision-making

BBNs have only been applied in a handful of studies within climate adaptation, their potential benefits were clearly identified via numerous calls for further research and application of the method to support adaptation, as highlighted in Section 3.5 (Catenacci & Giupponi 2010; Richards et al., 2013; Sperotto et al., 2017). Apart from the contribution of Richards et al. (2013) there has been limited critical assessment of the usability of BBNs for adaptation decision-making within a local authority. This research therefore seeks to contribute to this area. This section discusses the strengths and weaknesses of the BBN method in relation to climate adaptation decision-making at the city level. This discussion is based on data collected during the BBN development process including: reflections from participatantobservation, three expert elicitation sessions which included feedback on process, and one interview with the decision maker. Four benefits of using a BBN to support adaptation decision-making were identified. These include (i) visualising cause and effect relationships; (ii) integrating data sources; (iii) assessing potential effect of adaptation options; and (iv) performing ‘what if’ experiments. Each are explored below.

**Visualising cause and effect relationships** - The first noted advantage of the BBN was the ability to visualise cause and effect relationships. The decision-maker and two of the experts, stated that the visual element of the BBN was useful for aiding understanding of the complexity of the situation. The BBN output is also a user-friendly graphical representation (Morgan et al., 2009). BBNs therefore may be well placed to address the critique of current approaches which illustrate a variety of variables but are not clear on the assumed interactions and dependences between these variables (for instance adaptive capacity measurements) (Oberlack, 2017). Observations showed interest and enthusiasm in the process of creating the network structure interactively at the workshops and stakeholders found physically moving variables to consider relationships between them useful.

**Integrating data sources** - The second identified advantage was how the BBN integrated knowledge and data from multiple sources, addressing existing knowledge and data limitations. BBNs are able to incorporate empirical data and subjective (belief) data (S. H. Chen & Pollino, 2012). Within this research, the BBN provided a structured framework to bring together different types of knowledge in a situation with a lack of data (as experts provided judgements where information was not available). Whilst climate impacts are usually physical and can be quantified directly, concepts such as adaptive capacity and resilience are social processes which depend on the perceptions of stakeholders (Adger, 2003). Roiko et al. (2012) argues that the local context specific circumstances of adaptive capacity are not always captured in indicators or frameworks. Within this BBN study, the network was populated by stakeholders with knowledge and experience in emergency response, flood risk management and climate change adaptation in Glasgow specifically. The decision maker found the ability of the BBN to incorporate local knowledge beneficial.

**Assessing Options** - Thirdly, the BBN enabled the exploration of effects of potential adaptation options. The network helped the decision-maker consider the effect of different options and combination of action options. Expert #2 commented that the flood risk management sector in Scotland still was overseen by “traditionalists” who favoured infrastructure interventions and saw their role as flood prevention. This is in opposition to the increasing shift of flood practitioners seeing their role as part of wider place-making agenda. It was thus suggested by expert #2 that the BBN process may help flood risk management (FRM) practitioners consider broader outcomes and multiple benefits of actions and therefore may be useful from a decision-making perspective. The GCC decision-maker also stated, “today’s interview was helpful to think about detail, wording and impact of actions and I would use as a tool to appraise options – maybe it’s a good method to engage colleagues. At GCC we have vision but don’t consider how actions will help us achieve this vision. The BBN helped change thinking and having an external person query helps me consider actions, appropriateness of strategy. It [the BBN] helps you to analyse actions and think about things differently”.  This supports the proposal by Maskrey et al. (2016) that BBNs can help users see how different aspects of the system are interlinked or how multiple interventions may be needed to achieve set objectives.

It may be straightforward for a decision maker to identify potential risks and relevant adaptation options, but it may be more challenging to combine the information on potential options together to identify optimal decision. The BBN does this by computing the expected utility of the decision options.  Whilst the adaptation options assessed in the BBN all resulted in increased utility values (albeit to varying degrees), this is not always the case. Some actions may have negative consequences, which would be represented in the network as decreasing utility values. In this regard, BBNs can help illustrate the risk of maladaptation. Barnett and O’Neill (2010, p.211) define maladaptation as “action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups”.

The ability to explore how the adaptation actions influenced the utility of the BBN sections (exposure, adaptive capacity and public sector insitutions) was found by the decision-maker to be useful. The BBN allowed the consideration of how each option affected exposure or adaptive capacity utility, and how the packaging of options influenced overall flood resilience utility. Assessing how options altered the resilience of public sector insitutions supported consideration of internal adaptation actions needed. According to Fünfgeld et al. (2019, p.637) there is a need for “reflection on how organisational culture, structures and governance can constrain adaptive capacity of the organisation itself, and the stakeholders they support.” The BBN supported this.

**Performing ‘what if’ experiments** – The BBN also allowed the exploration of future scenarios through ‘what if’ experiments. The network can be adjusted to consider potential climatic changes as well as possible socio-economic scenarios. This strength helped consider different levers in the system to inform decision-making as well as highlighting the uncertainty present. Therefore, a benefit of BBNs is their ability to incorporate and communicate uncertainty. The probabilistic expression of knowledge within BBNs incorporates uncertainty (Sperotto et al., 2017). The joint probability distributions within a BBN represent beliefs and are therefore seen as expressions of subjective uncertainty (Sprenger & Hartmann, 2019). Uncertainty can be reduced as new information based on data is improved, informing variables within a BBN. Climate adaptation planning necessitates continuous updating of information of interventions and climate conditions. BBNs are flexible and allow new knowledge to be integrated by updating probability distributions which then flow information between variables in the network. This continuous learning is seen as advantageous for adaptation. BBNs thus may be well placed for enabling principles of adaptive management and support iterative process of learning and reflection, an important element of managed adaptive practices. This was seen as advantageous by the decision-maker, however the limited resource availability and capacity to maintain such a network was highlighted.

There were, however, limitations identified relating to the application of BBNs to climate adaptation decision-making based on this action research study. Limitations identified included: (i) the availability of appropriate experts; (ii) elicitation burden; (iii) potential bias; (iv) the need for facilitation and modelling support and (v.) the need to incorporate time into the network.

**Availability of experts -** To be able to undertake expert elicitation, there must be availability of and access to experts who can provide informed judgements on the subject matter. It is recognised that people may have knowledge of an area, but not be able to make informed predictive judgements. Morgan (2014 p.7176) states, “the further one moves away from questions whose answers involve matters of fact that are largely dependent on empirical natural or social science and well- validated models, into realms in which individual and social behaviour determine the outcomes of interest, the more one should ask whether expertise, with predictive capability, exists.” Experts with the correct experience and insight must be available and accessible. Experts involved in this research had technical skills and professional experience pertaining to the BBN (such as flood risk management and adaptation planning), however all did not possess the numeracy to easily participate in the BBN development process. This highlights the potential elicitation burden associated with BBNs.

**Elicitation Burden –** This research found that there was a high elicitation burden of consulting experts to populate the BBN. The technical skills required to understand and appreciate the model were noted by Expert #1. They said, “my eyes tend to gloss over when you talk math or probabilities to me. I’m still to be convinced by a model – I’m not numerical – think it’s more emotional – more instinctive knowing how to respond to events.” Similarly, Expert #2 said “well originally I thought I’m going to be quite dispassionate about it and do it on mathematical basis but it’s hard not to bring in feelings and gut reactions.” Expert’s knowledge of the probability of causes and effects may be strong, however their numerical skills to formalise this knowledge with elicited probabilities to populate CPT may be limited as suggested by Castelletti and Soncini-Sessa (2006). All experts did get faster in eliciting values during the elicitation interview as it went on, demonstrating how familiarity eases burden and alluding to the benefits of additional training. The visual element of the BBN was found by the decision maker to be more compelling than the quantitative data. This may be due to the competence and comfort of the staff member in working with quantitative data.

**Bias -** When humans make judgements in situations of uncertainty, a range of cognitive heuristics are used which may introduce bias (Morgan, 2014). In terms of precision within this research, experts reflected that the numerical figures provided were based on past experience and gut reaction. The numbers provided were ballpark estimates, and the experts could not guarantee they were 100% accurate. It was recognised that the inclusion of utility values, encouraged the decision-maker down a path of rationality (which as Section 6.5 highlighted is challenging for adaptation).

**Facilitation -** There was also an identified need for support in developing and using the BBN. The adaptation decision maker at GCC reflected that they felt the BBN process was challenging but useful. They found initially it was slightly overwhelming, but it became clearer over time when using real proposed adaptation actions, as they stated: “Overall it can be a bit daunting but at local level its clear, it’s easier when you talk me through it”. This highlights the important role of the researcher / network builder as an active facilitator and knowledge broker, and this study found that communicating in a clear and accessible manner was key. As such, there is a required dedicated role for support throughout the BBN development process.

**Further requirements of BBN -** Additional shortcomings of the BBN output identified by experts involved in elicitation process related to the need to include temporality within the network. The example was given, that if a flood happened at night-time some elements such as people and domestic properties may be more adversely affected. The daily variance within a day as well as difference between weekdays and weekends was also seen as influential to flood resilience. This limitation could be addressed by the use of Dynamic Bayesian Networks which incorporates temporality through multiple time steps (Ghahramani, 1998). Challenges in representing temporally and spatial dynamics could be addressed by accompanying GIS coupled with BBNs to visualise outputs spatially as the case in Balbi et al. (2015), Grêt-Regamey & Straub (2006) and Gutierrez et al. (2011). Further assessment of the BBN, specifically in relation to challenges identified in Chapter 6, is offered in Chapter 10.

## 8.4 Conclusion

This chapter presented the results of the construction and use of a BBN to support decision-making on pluvial flood resilience in Glasgow. The qualitative network of the

BBN was constructed with the input of twelve stakeholders. The network was quantified via three experts populating CPTS of the variables they were most familiar with, before being validated by GCC's adaptation lead, the primary decision maker. In summary, the key strengths of BBN development and application within the climate adaptation context in this study included aiding system understanding; incorporating different data types; option analysis and the ability to explore effects of adaptation interventions. Noted important challenges or limitations in this study included availability of experts, elicitation burden, bias and facilitation requirements.

Due to my relationship with GCC as well as their ongoing strategy development process, there was an opportunity to undertake a second study with stakeholders to explore alternative methods and approaches. Through discussions with the adaptation lead, it was identified that currently no actions existed in the adaptation action strategy that dealt with heat, overheating or heatwaves as no proposed actions responding to this risk were identified at the August 2017 workshops. The Summers of 2018 and 2019 experienced heatwaves with widespread consequences for Glasgow such as buildings overheating and travel disruption. Extreme heat events are also projected to increase in the future (O'Neill & Tett, 2019; Undorf et al., 2020). The lack of inclusion of heat risk and related adaptation interventions was acknowledged as a key gap in the draft adaptation action plan by the decision maker.  Thus, the second study sought to test the design and implementation of a decision support method to identify and appraise adaptation options for managing heat risk which had less of an elicitation burden and technical requirements and less facilitation expertise needed, than the BBN approach had. The next chapter (9) introduces how a qualitative probabilistic network (QPN) for heat resilience was developed and tested.

# Chapter 9: Exploring application of Qualitative Probabilistic Networks to support heatwave resilience decision-making

> "The increasing number of knowledge-based systems that build on a Bayesian belief network or influence diagram acknowledge the usefulness of these frameworks for addressing complex real-life problems. The usually large number of probabilities and utilities required for their application, however, is often considered a major obstacle. The use of qualitative abstractions may to some extent remove this obstacle."
> (Renooij & Gaag, 1998, p.1)

This chapter presents the second decision support method studied in this thesis, which was QPNs. QPNs were selected due to their novelty in application within adaptation decision-making but also because they possess the same traits that were identified as positive in the BBN approach, being a visual tool, that supports identification of causal relationships to aid system understanding and inform decision-making. The lack of quantitative elicitation associated with QPNs was anticipated to address the elicitation burden identified in the BBN study. This second study was informed by lessons learnt from the first (BBN study presented in Chapter 8). This is an important aspect of action research, the ability to consider changes and refine research based on local context, experience and feedback (Reason et al., 2015).

A step-by-step account of the research methodology used to build the QPN and evaluate the process, is presented in Section 7.4. Three phases were undertaken including: (i) Phase One: constructing the qualitative network structure; (ii) Phase Two: eliciting synergies and strengths of relationships within network; and (iii) Phase Three: analysis. This chapter presents outputs and associated findings from each stage.

The remainder of the chapter is structured as follows: the QPN study on heatwave resilience across the three research phases is presented as Section 9.1 introduces Phase One and the qualitative network, Section 9.2 describes Phase Two and the identification of influences and Section 9.3 presents Phase Three analysis of the QPN. Section 9.4 reflects on the advantages and limitations of the QPN approach. Finally, Section 9.5 concludes the chapter and argues for the use of QPNs to complement quantitative approaches to inform adaptation decision-making.

## 9.1 Phase one: identifying variables for the qualitative network

The first phase of QPN development was to develop the qualitative network. The QPN constructed in this chapter is applied to the topic of heatwaves. Although historically overlooked as a risk in Glasgow, heatwaves are already having impacts on the city and their frequency and intensity is projected to increase in the future (O'Neill & Tett, 2019). For example, the 2018 summer heatwave that occurred across the UK had widespread consequences across Glasgow ranging from transport delays to adverse health conditions (Undorf et al., 2020). Climate change means that this may become the 'new normal' with research indicating that by 2050 every other summer in Glasgow will be similar to that experienced during the heatwave of 2018 (Undorf, 2019).

*Figure 9.1: Photographs of stakeholders constructing the qualitative network*

As discussed in Section 7.4, the IPCC AR5 framework was used to structure the network. Use of the framework as a discussion prompt, led to stakeholders identifying twenty-five different impacts relating to heat waves in Glasgow. Impacts were grouped based on hazard and then prioritised by stakeholders. This resulted in two hazards being identified as of interest for further exploration: (i) overheating of buildings and

(ii) changes to the public realm. The following images illustrate the workshop exercise process (Figure 9.1) and the identified variables for the initial networks (Figure 9.2).



*Figure 9.2: Photographs of the handwritten variables for the network exploring overheating of buildings as a hazard (top image) and changes to use or function of public space (bottom image). The orange post-it notes represented exposure variables, blue represented sensitivity and yellow represented adaptive capacity variables. The impacts were captured in pink post-it notes at the bottom. Proposed actions were recorded on white template sheets and placed closest to the variables they pertained to.*

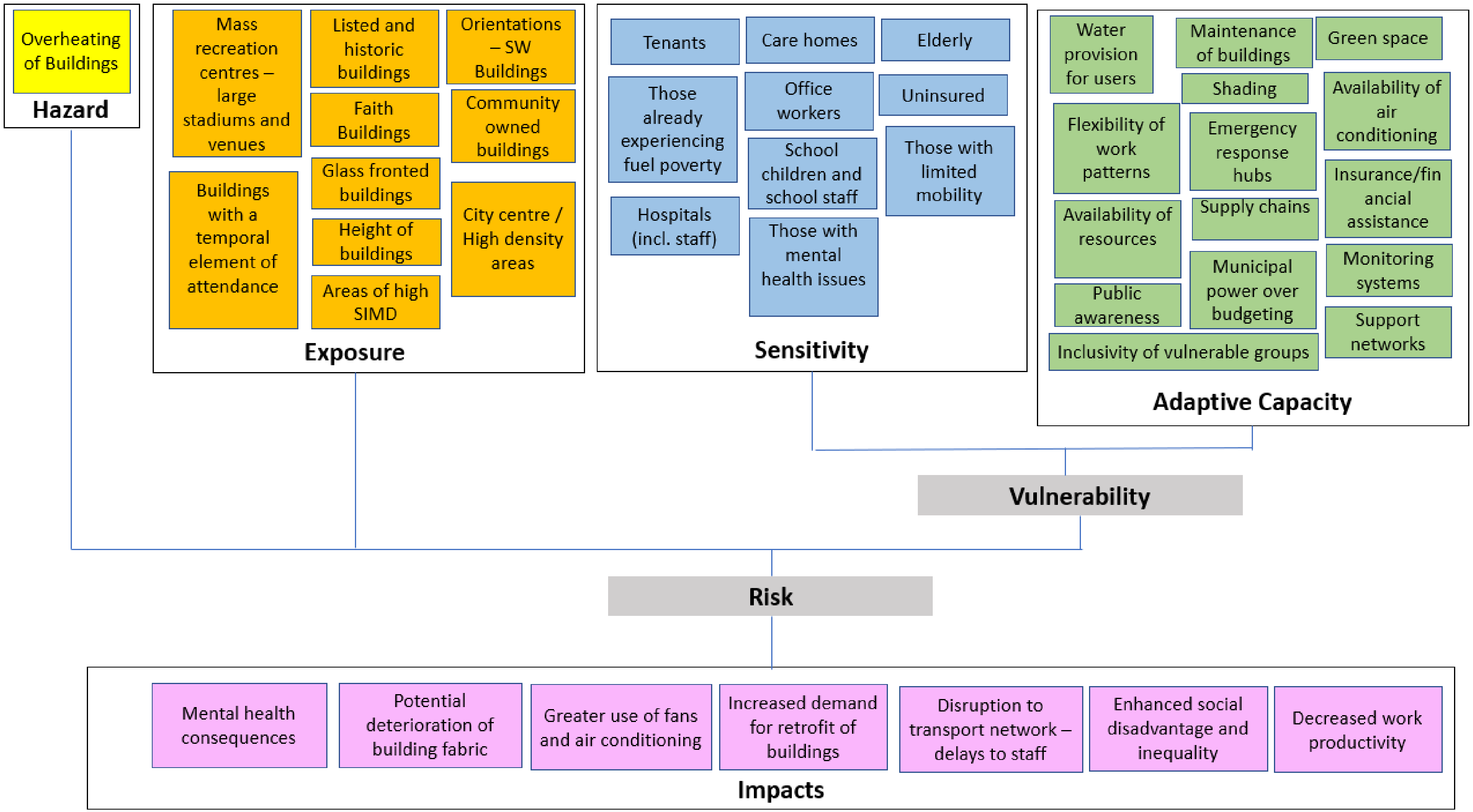
Phase One identified variables related to each hazard in relation to exposure, sensitivity and adaptive capacity. The process aided understanding of the elements which interact to result in climate impacts driven by each hazard. Identification of these variables by stakeholders allowed local knowledge of the hazard to be captured.

The identification of variables relating to 'overheating of buildings' provided a representation of the problem in Glasgow (as shown in Figure 9.3). For instance, in relation to exposure particular buildings such as mass recreation centres (e.g., Hampden Football Stadium, SECC and the Hydro) were highlighted, as well as listed and historic buildings (of which there are over 1800 in Glasgow), glass fronted buildings (with the example of GCU's recently built glass campus buildings overheating being cited), as well as those buildings in areas of high Scottish Index of Multiple Deprivation (SIMD) and high-density areas. These variables were suggested directly by attendees, however, are also supported by available literature. McLeod and Hopfe (2013) found there is significant overheating risk in highly insulated buildings in Scotland. Morgan et al. (2017) found that 54% of homes studied experienced overheating for over six months of the year. Impacts of heatwaves are also often more prevalent in urban areas due to the urban heat island effect (Andersson-Sköld et al., 2015).

The discussion also identified which groups were believed to be most sensitive to potential heatwaves. Heatwaves can cause diverse impacts. Intense heat events or heatwaves can result in severe illnesses, loss of productivity and in some case death. Certain individuals and groups are more at risk of heatwaves for instance elderly populations, those living alone or experiencing social isolation, those with pre-existing health conditions or those on medication which affect thermal regulation or heat perception (Andersson-Sköld et al., 2015). Variables identified support these findings, with the inclusion of the elderly, care home residents, those in hospital, with limited mobility and pre-existing physical and/or mental health conditions, within the network (as seen in Figure 9.3). The stakeholders highlighted the need to consider these groups in the context of wider socioeconomic changes as well. For instance, as the population not only expands but ages, the risk of premature heat related deaths and illnesses may occur due to increased populations at risk.

The third element that was explored was adaptative capacity. Stakeholders suggested that adaptive capacity (to deal with overheating in buildings) was affected by flexibility of work patterns, availability of resources, levels of public awareness, monitoring, support networks, water provision, emergency response hubs, maintenance of buildings, shading and access to green space (Figure 9.3). These suggestions supported the recent findings of Majekodunmi et al. (2020) which demonstrated that deprived communities within Glasgow City are more likely to be impacted by heatwave impacts, than compared to more affluent areas, due to variances in green infrastructure. All variables identified for inclusion in the network are shown in Figure 9.3.

*Figure 9.3: Output of workshop 1 – identification of variables for QPN using IPCC AR5 Structure.*



The second hazard explored was changes to use and function of the public realm, or publicly accessible urban spaces (as shown in Figure 9.4). Variables identified relating to exposure included housing type, city centre, quality of green open space, biodiversity, areas of high SIMD, whilst variables of sensitivity related to age (infants and elderly), ethnic and minority groups, mobility, and access limitations. In terms of adaptive capacity, it was identified that planning policy, political leadership, data availability, public awareness, local decision-making processes, social capital, resources, and the restoration and use vacant and derelict land were all important (Figure 9.4). Impacts associated with the hazard included increased maintenance, enhanced use of public space, economic costs, health consequences and effect on air quality. Thus, this activity elucidated what stakeholders felt affected and were affected by changes to use of the public realm due to heatwaves.

Identifying variables in Phase One was observed to be useful for stakeholders and the decision maker as it aided understanding of the two heatwave driven hazards. The sheer number of variables identified for each component of the network (in relation to both hazards) proved incredibly useful for understanding perceived influences on heat risk. Participant observation as a facilitator at the workshop, identified that the emphasis on building the qualitative network structure proved useful, with rich and lively discussions amongst participants on the topic. Participants came from different departments and backgrounds, and all contributed different viewpoints and thematic expertise.

It was also observed that Phase One helped begin to bridge the divide between academic language and practitioner insight. Significant time was provided for stakeholders to learn about and explore the different concepts of exposure, adaptive capacity, and sensitivity, as many were unfamiliar with these terms. However, stakeholders were knowledgeable about these elements in practice (e.g., health representative was knowledgeable about which populations, areas and groups may be particularly vulnerable), just not using the academic terms (such as exposure or sensitivity). Having knowledgeable, experienced stakeholders involved in group discussion, was found to be helpful for variable identification and insight.

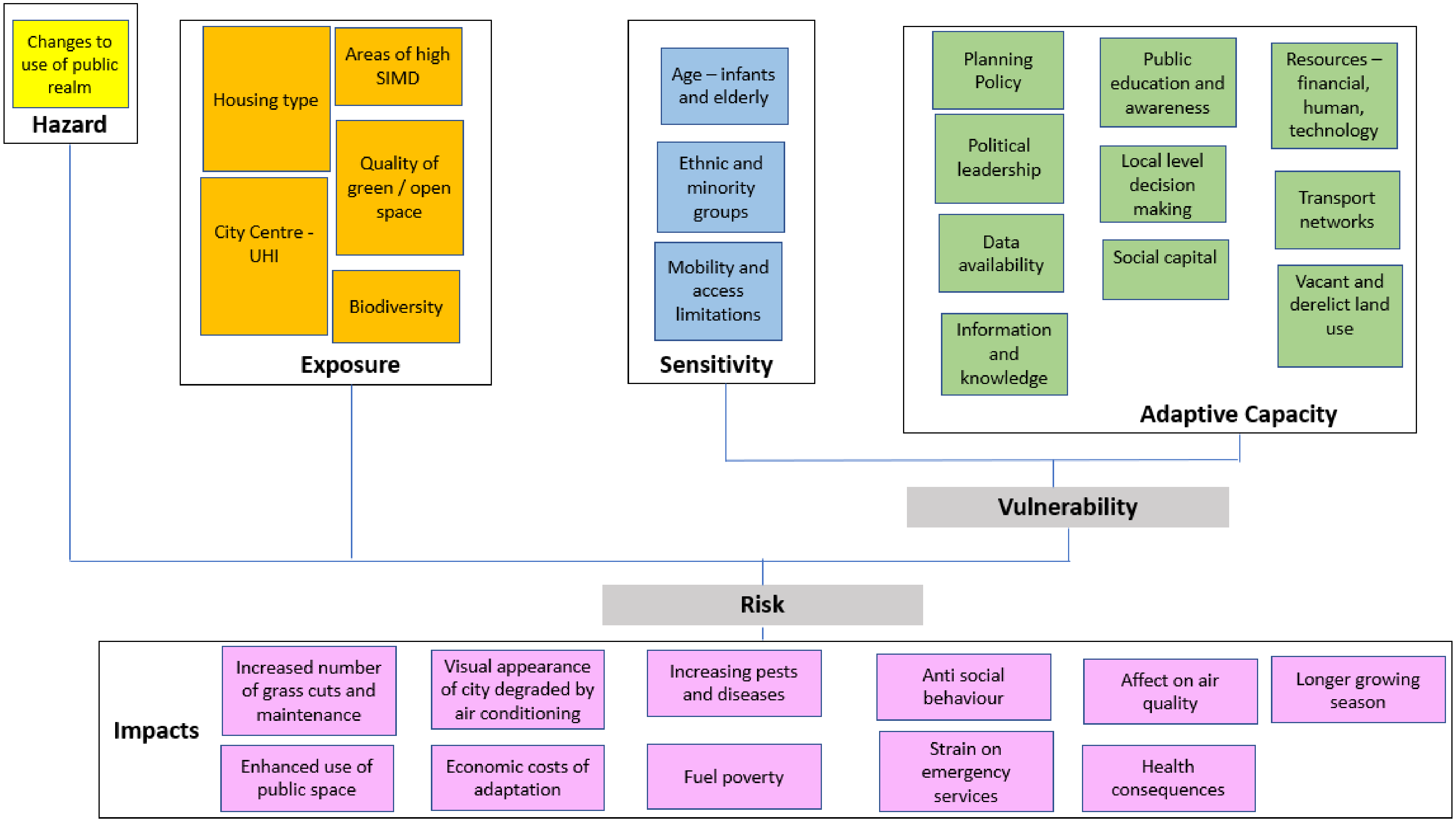



*Figure 9.4: Identification of variables for changes to use of public realm network*

## 9.2 Phase Two: eliciting synergies and strengths of relationships within network

The second phase of the QPN development was to identify and explore the relationships between variables within the network developed in Phase One. Following the Phase One workshop, the variables from both networks were combined and restructured hierarchically. The decision to combine the content from workshop one (overheating of buildings and changes to public realm) was due to the decision-maker wanting to explore the problem holistically and examine solutions which had co-benefits (potentially spanning across problem areas). The restructure was based on the structure to support decision-making proposed by Fenton and Neil (2001), which identified an objective of decision-making, influenced by criteria and sub-criteria. In this case, the objective was to ensure Glasgow was resilient to heatwaves, the criteria were the extent of exposure, sensitivity and adaptive capacity and the sub-criteria were the variables stakeholders identified that influence these concepts. The hierarchical structure produced is shown in Figure 9.5.

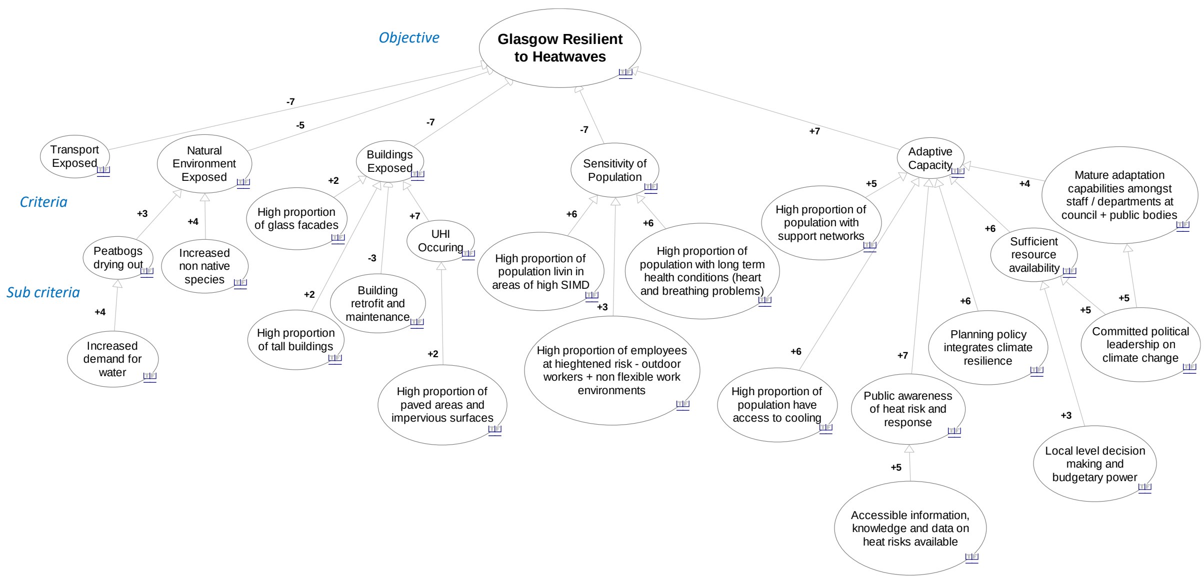



*Figure 9.5: Schematic illustration of how QPN network was reconfigured hierarchically for further discussion and refinement during phase two*

Phase Two involved a second workshop with stakeholders (the same ones who attended the first workshop). During this phase, additional influences and strength of influence information was added between the identified variables in the network. The causal relationships were identified via discussion using qualitative terms of either positive (causes), negative (barriers) or uncertain (unsure).

The discussion was had in plenary, and type and strength of influences were decided on collectively (by reaching consensus verbally). Workshop participants found this process relatively intuitive and were very forthcoming with their opinions on relationships. The attribution of causal relationships between nodes was based on lived experience and background knowledge or information where appropriate. Annotations regarding the strength of influence, were then added to the printed network structure worksheets, whilst notes from discussion recorded in action research notebook. The following figures show this process. Figure 9.6 is a photograph of stakeholders at the workshop and Figure 9.7 shows the process of adding annotations. Figure 9.8 provides a summary of the results of the workshop (and Phase Two) which is an annotated network.

In terms of reflections from Phase Two, it was observed that the concept of qualitative influences was a challenging but impactful aspect of the workshop. It took more time than expected to introduce and explain influences to the participants, as there were many questions, however they said it was interesting to reflect on. Adequate time and examples are needed for participants to be comfortable with these concepts.

*Figure 9.6: Photograph of stakeholders at second workshop annotating QPN by adding influence relationship types and strengths*

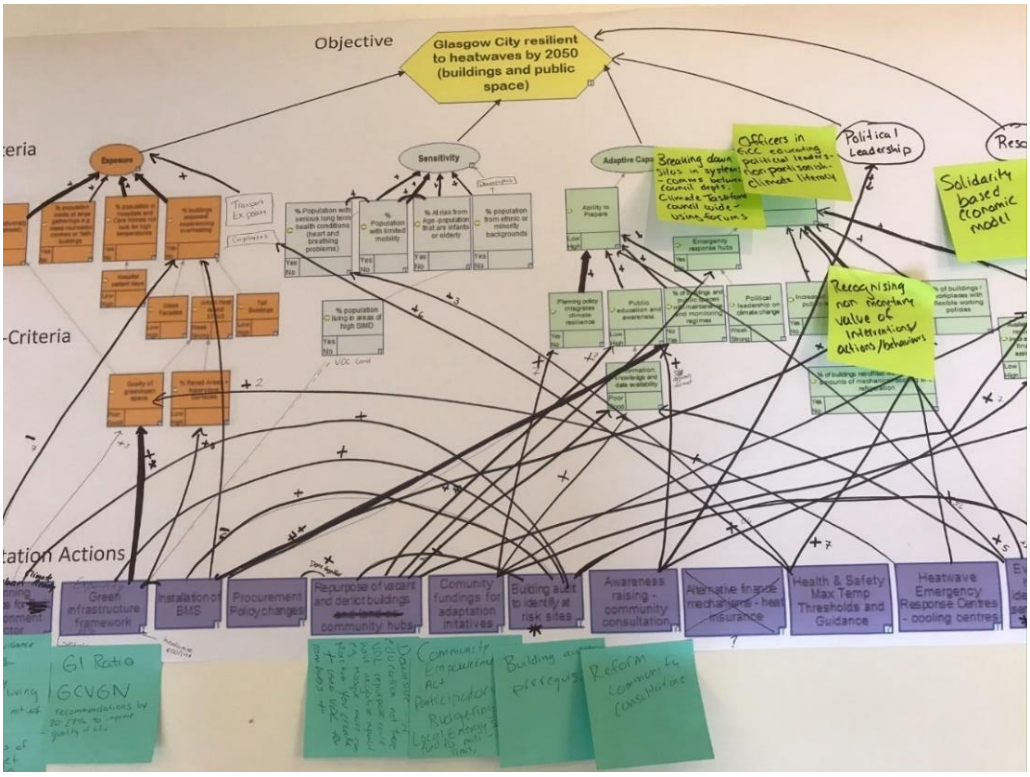



*Figure 9.7: Photograph of the output of workshop two -an annotated hand drawn network. The lines show type of influence. The annotated numbers illustrate strength of influence.*

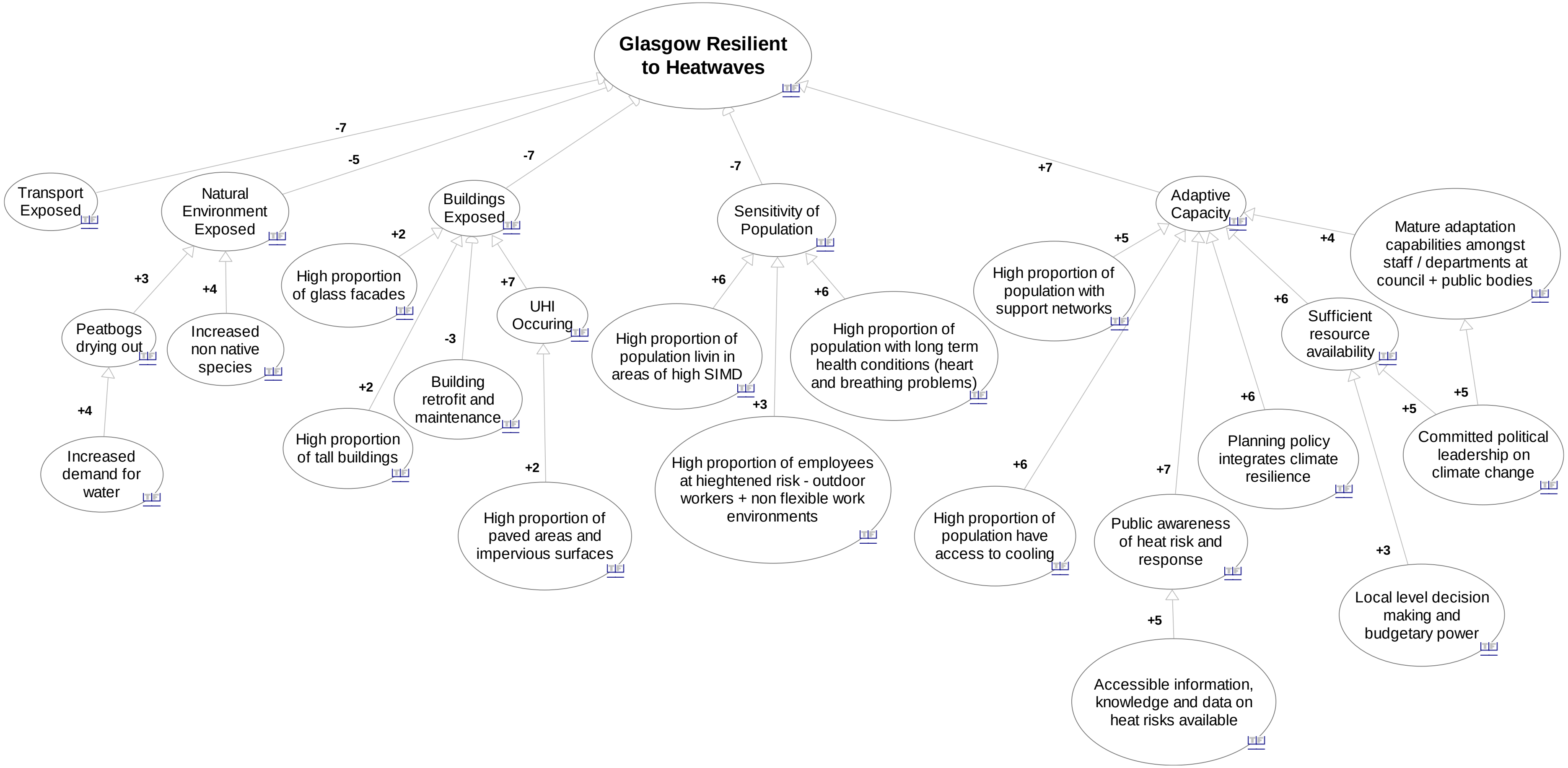



*Figure 9.8: QPN at the end of phase two showing type of influences (represented by type of arrow heads – triangular heads reflect causes and rounded heads barriers) and strength of influences (represented by numerical annotation on a scale of 1-7 with 1 being very weak and 7 being very strong). Negative relationships were indicated by negative strength annotation, e.g. -7, whereas positive relationships were indicated by positive number annotation.*

## 9.3 Phase Three: analysis of the QPN

Phase three involved using the QPN to (i) identify and (ii) appraise potential adaptation actions to minimise risk and enhance resilience to heatwaves. Adaptation actions (both ongoing and proposed) were identified via workshops during both Phase One and Two. The QPN supported options identification by highlighting variables which either adversely or positively influenced resilience to heatwaves in Glasgow. Phase Three appraised eleven potential adaptation actions in total.

Following identification of options, stakeholders were prompted to consider which variables or nodes in the network the action would affect. This highlighted that many actions were believed by stakeholders to influence multiple variables, illustrating the co-benefits of the intervention. Like Phase Two, the strength of the influence the action exerted on variables was elicited and recorded. This strength is represented via numerical annotation (Figure 9.9).

The QPN thus supported options evaluation, as well as identification. Through structuring knowledge of system and causality one can explore ‘what if…?’ type questions such as ‘what if we implemented maximum thresholds for working conditions, what does this mean for resilience to heatwaves?’. The result reflected stakeholder perceptions about which variables each action affected and to what extent (relationship and strength of influence). In this way, the network illustrated pathways to achieve the objective of Glasgow being resilient to heatwaves. For instance, Figure 9.9 highlights which actions were identified as having very strong positive influences on nodes in the network, and how then affected related causal relationships. To note, that the network is based on the implicit assumption that a heatwave will occur. There are no specifications of the severity of the heatwave. The stakeholders involved in the development of the network and the decision maker are therefore assessing the value of taking action to enhance resilience, given a heatwave event.

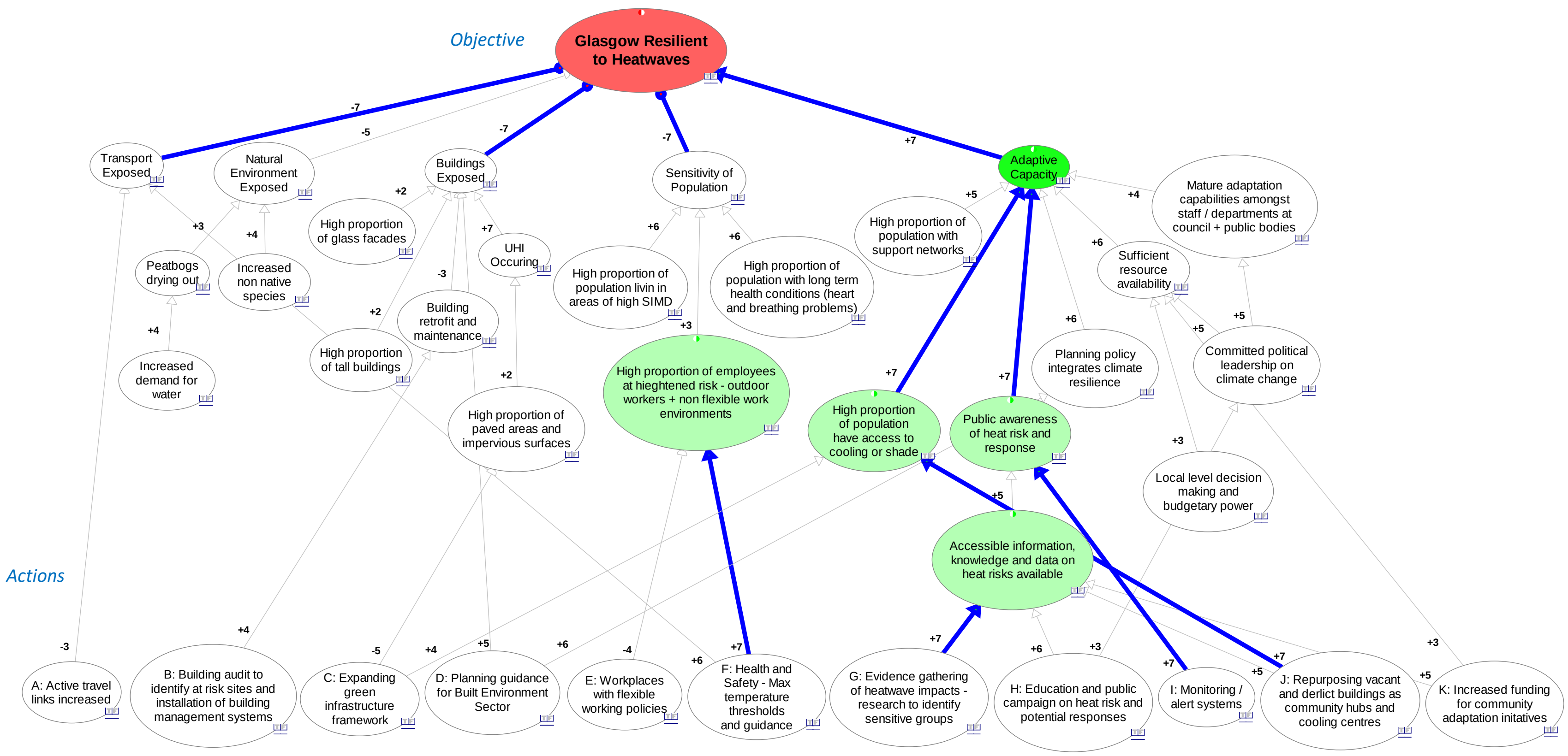



*Figure 9.9: QPN based on stakeholder perception on influence and strength of influence of potential adaptation actions on variables within the network. Blue arcs represent the strongest positive relationships contained in the network. The green nodes illustrate nodes which were positively affected by actions. The objective node is red as it is believed to be in a current false or undesirable state. To note QGenie does not use the notation of square boxes for decision nodes as is common in BBN practices.*

In addition, synergies between actions were identified and quantified (using a verbal qualitative scale of very weak to very strong, which correlated with numerical annotations on a scale of 0-7). This helped highlight the advantage of taking multiple actions in tandem to achieve greater benefits. Table 8.4 shows the identified synergistic relationships between actions.

For example, Option B building audit to identify at risk sites and installation of building management systems, had strong synergies with Option D planning guidance for built environment sector and Option F health & safety maximum temperature thresholds and guidance. This may be due to perceived advantages of planning guidance encouraging or supporting building audits, and the installation of building management systems enabling the monitoring of temperatures and warning if thresholds exceeded. Similarly, Option G evidence gathering of heatwave impacts and accompanying research to identify sensitive groups was found to have strong synergies with Option H education and public campaign on heatwave risks and responses and Option K, increased funding for community adaptation activities. Such synergies may be as a result of potential benefits arising from Option G in evidencing and understanding which groups are most sensitive to heatwaves to inform targeted focus of public campaigns and funding initiatives. Observations and conversations with the decision maker showed clear benefits of being able to identify synergistic relationships to support adaptation decision-making to understand and take advantage of co-benefits arising from implementing suite(s) of actions together.

*Table 9.1: Synergies between potential adaptation actions, identified by stakeholders. Shades of green represent the strength of the synergy between actions. Blank / no colour boxes reflect that no relationship between these actions was highlighted by stakeholders. The same 1-7 score from Phase Two was used with 1 being very weak relationship and 7 being a very strong relationship. Where no numbers are recorded, no synergistic relationships were identified.*

| | Option A Active travel links increased | Option B Building audit to identify at risk sites + installation of building management system | Option C Expanding green infrastructure | Option D Planning guidance for built environment sector | Option E Workplaces with flexible working policies | Option F Health and safety – max temperature thresholds and guidance | Option G Evidence gathering of heatwave impacts + research to identify sensitive groups | Option H Education and public campaign on heat risk and potential responses | Option I Monitoring / alert system | Option J Repurposing vacant and derelict buildings as community hubs and cooling centres | Option K Increased funding for community adaptation initiatives |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Option A Active travel links increased | | | +5 | +6 | | | +3 | +5 | | | |
| Option B Building audit to identify at risk sites + installation of building management system | | | +5 | +7 | | +7 | +2 | | | +5 | |
| Option C Expanding green infrastructure | +5 | +5 | | +5 | | | +5 | +5 | | | |
| Option D Planning guidance for built environment sector | +6 | +7 | +5 | | | | +3 | | | +5 | |
| Option E Workplaces with flexible working policies | | | | | | +5 | | +6 | | | |
| Option F Health and safety – max temperature thresholds and guidance | | +7 | | | +5 | | | | +7 | | |
| Option G Evidence gathering of heatwave impacts + research to identify sensitive groups | | +2 | +5 | +3 | | | | +7 | | | +7 |
| Option H Education and public campaign on heat risk and potential responses | | | | | +6 | | +7 | | | | +4 |
| Option I Monitoring / alert system | | | | | | +7 | | | | | |
| Option J Repurposing vacant and derelict buildings as community hubs and cooling centres | | +5 | | +5 | | | | | | | +7 |
| Option K Increased funding for community adaptation initiatives | | | | | | | +7 | +4 | | +7 | |

Given the context and findings from BBN study (Chapter 8) indicating that stakeholders found providing probabilistic information challenging and burdensome, such information was not sought from stakeholders in the QPN study. Only qualitative information was requested, for example the type of influence and strength of influences and synergies. This level of information produced Figure 9.9 which identified adaptation options which had a strong and positive influence on nodes in the network. The resulting output, Figure 9.9, helped illustrate cause and effect relationships and highlight potential pathways to achieve the objective of Glasgow being resilient to heatwaves. To this point, the process with stakeholders was solely qualitative and participatory (the network was a reflection entirely of their input) (as discussed in Section 7.5.3).

Following the workshops, however, I further developed the network in QGenie (a QPN software application). Within the QPN developed, nodes took the form of either (i) parent nodes which are populated with prior probabilities; (ii) child nodes which are affected by influence and strength of influence of parent nodes; and (iii) action nodes which can turned on or off by setting evidence to true or false. Within QGenie, I populated the prior probabilities of parent nodes based on a combination of insight from stakeholders and existing datasets. I then input the strength of influence information stakeholders had provided (illustrated by variable arc widths). Next, I turned the different interventions on or off, i.e., setting the evidence to true or false to observe what happened (shown in Figure 9.10). This highlighted the effect of actions on the objective of Glasgow being resilient to heatwaves. The results corroborated the discussion at the workshop which highlighted the same actions that were most effective (i.e., had a strong positive relationship) on achieving the intended outcome of resilience to heatwaves. These actions span both building capacity and on-the ground delivery adaptation actions and included:

(i) planning guidance for the built environment (Option D),
(ii) implementing max temperature thresholds for workers (Option F),
(iii) evidence gathering of experience impacts and research to identify sensitive groups in Glasgow (Option G),
(iv) introduction of a heat wave alert and warning system and (Option I)

(v) Repurposing vacant or derelict buildings as community centre cooling hubs (Option J).

The resulting QPN is shown in Figure 9.10 and descriptions of underlying nodes and data used to populate parent nodes is available in Appendix XIV. This quantified QPN was shared with the decision maker for information and comment. A further workshop to seek feedback from wider stakeholders did not take place, as the second workshop took place Feb 2020. Just a few weeks later the first COVID 19 lockdown came in to place in the UK and many of stakeholders involved were furloughed and thus unable to contribute to this research process. The intention of the QPN study had always been to engage stakeholders in the qualitative network development, not the quantification elements (as discussed in Section 7.4.1), so this set back did not significantly alter the intended approach but did limit wider validation and further feedback opportunities.

The QPN developed is presented in Figure 9.10. This shows the effect of all potential adaptation options on the network. This visual summary indicates that 7 of the 11 proposed actions influence adaptive capacity, 3 actions that influence nodes affecting exposure and only 2 actions which relate to issues affecting sensitivity of the population. This information can illustrate missed opportunities or needed actions, by considering which nodes are not being addressed by proposed actions. The exercise also reveals possible bias of stakeholders, with a preference for actions which enhance adaptive capacity or reduce exposure over those which deal with sensitivity. This may indicate a reluctance for systemic change that addresses root causes of risk, with a preference for siloed, incremental activities.

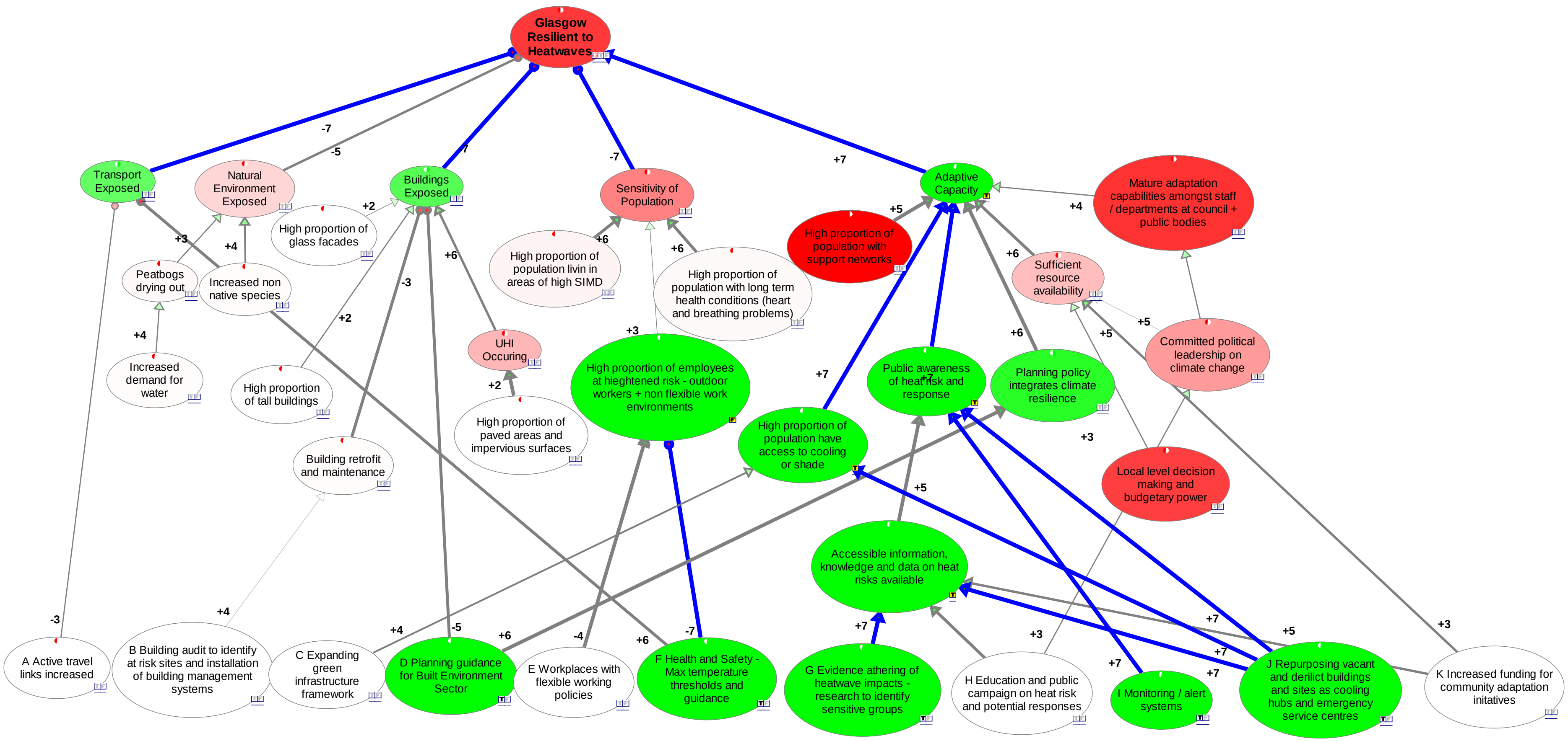



*Figure 9.10: QPN at the end of phase two highlighting the five actions identified as most effective for achieving climate resilience (to heatwaves) denoted by green colouring. These options were identified as most beneficial given the different variables each would positively affect and the strength of the influence, as denoted by the annotation and width of arc. This QPN contains prior probability information of parent nodes, populated following workshops.*

Figure 9.11 presents a graph illustrating the effect each adaptation action (or combinations of actions) would have on the probability of Glasgow being resilient to heatwaves. Analysis illustrates that Option F and G are the best performing options to achieve the objective. Information also indicates that the decision-maker would benefit from undertaking a combination of actions that target elements of exposure, sensitivity and adaptive capacity as actions are needed across all areas to achieve heatwave resilient. For instance, combining G with H or K does increase the probability of resilience, supporting the idea of a synergistic relationship between these actions identified in the workshop in Phase Two (Table 8.4). The increase, however, is not as great as other combinations which influence nodes across the network, including building exposure, sensitivity, and adaptive capacity. For example, a combination of DFJ (which span building exposure, sensitivity, and adaptive capacity nodes) would lead to a 40% likelihood of resilience, not far off the 45% achieved via undertaking all proposed actions. Some combinations (such as D and I or F and G), were not identified as having strong synergies (Table 8.4) but do appear to lead to greater chances of resilience when combined (Figure 9.11) as each action influences different nodes across each section of the QPN. To note, these results and associated analysis are illustrative to explore QPNs as a 'proof of concept' in relation to climate adaptation.

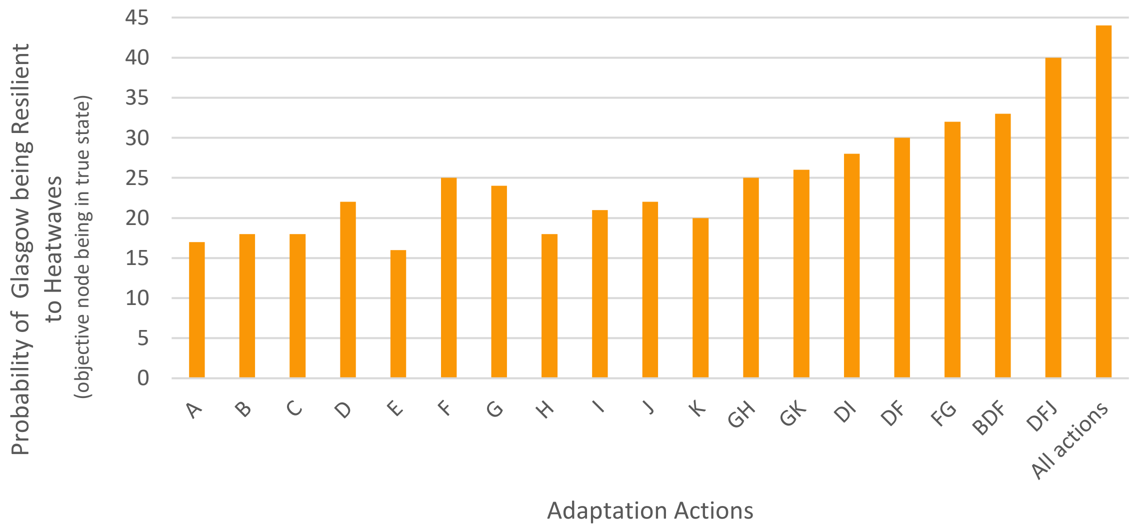



*Figure 9.11: Graph of effect of adaptation actions on probability that Glasgow will be resilient to heatwaves (the objective node being in a true, or positive, state)*

## 9.4 Discussion: Considering usefulness of QPNs for Climate Adaptation Decision-Making

The aim of this chapter was to assess how QPNs could support climate adaptation decision-making. Research on the perceived usefulness of QPNs to climate adaptation was achieved via focus group discussions at the end of each workshop during Phase One and Phase Two, a final questionnaire with those involved in the QPN development process and a semi-structured interview with the decision-maker. Learnings on the strengths and weaknesses of developing and applying a QPN for climate adaptation are offered in this section. Reflections are further discussed, in comparison to BBNs, in Chapter 10.

The first benefit of QPNs to climate adaptation decision-making found in this study was their role in supporting understanding of a problem. The network visualised the reasoning and assumptions pertaining to the hazard identified via the workshops. Therefore, the network represented shared collective understanding. The inclusion of synergies and influences were advantageous (in comparison to a causal map) as the network allowed more detail and the exploration of co-benefits.

A second observed benefit of QPNs is how they can inform decision-making on adaptation. QPNs can help with options identification and appraisal as the network enables interactive exploration, whereby the effects of observations or manipulations on individual variables can be assessed. The focus of reasoning within the QPN is not based on exact probabilities, but instead the type of influence and strength or order of magnitude of the effects. As Wellman (1986, p.311) states "while the conclusions are much weaker than those computed from complete probability distributions, they are still valuable for suggesting potential actions, eliminating obviously inferior plans, identifying important trade-offs and explaining probabilistic models." QPNs can thus be used to aid understanding of causal relationships to support understanding for strategic planning problems and explore the consequence of different decisions, as was discussed. The participatory modelling process used to develop the QPN facilitated the identification of adaptation options easily, with a significant number of options being proposed in a short amount of time. For example, the group exploring 'overheating of buildings' identified seven ongoing actions which addressed components of the model, either reducing exposure or sensitivity or enhancing adaptive capacity, and then reflecting upon gaps were able to propose ten new actions they felt were required.

The QPN enabled stakeholders to become engaged in discussions relevant to decision-making such as trade-offs, ensuring realistic bounding of the problem, acknowledge constraints on potential actions and identifying realistic outcomes. For instance, questionnaire responses to asking how stakeholders found the QPN process "enjoyed the structure of the process as it showed a large subject reduced to logical sections that stimulated conversation, allowing for the sharing of different experiences which added colour to the workshop". One respondent did note however that they "liked the structure but I think I would have benefitted from more explanation of the terms like exposure and adaptive capacity as they are still new to me". I suggest that QPNs can act as an excellent catalyst to start discussions to identify and assess actions in advance of a formal options appraisal process.

The third identified advantage of QPNs for climate adaptation decision-making at the city level was their (relatively) limited resource requirements. The QPN approach sought to develop a process which was easier or less cumbersome for experts and was better suited to the context of limited time and resource among experts and decisions makers (in comparison to the BBN approach used in Chapter 8). The time allocated during two workshops was 9 hours. During this time, the stakeholders collectively identified over 30 variables that influence heatwave resilience in Glasgow, used an understanding of the dependence relationships in the system to highlight 11 potential adaptation actions. This helped prioritise actions for inclusion in GCC's adaptation strategy.

Development of the QPN and analysis of proposed options helped inform GCC's decision-making. Glasgow City Council had not developed a heat wave response plan or included adaptation actions relating to heatwaves or overheating in their draft adaptation action plan at the point of this research. As such, the opportunity to use

QPNs to explore heat risk and resilience for Glasgow was welcomed by the adaptation lead. As a result, 3 new actions related to enhancing resilience to heatwave events were proposed to be included in GCC adaptation strategy and action plan demonstrating the value delivered from the QPN process (as previously no mention of heatwaves was included in drafts of the plan). An interview with the decision-maker identified that whilst they found the QPN development complex, they also saw it as useful and valuable. She found the QPN process and subsequent outputs beneficial and felt that the annotated network would help build legitimacy and get buy-in from colleagues to support adaptation.

The QPN approach was also found to be accessible to non-technical stakeholders. Participatory modelling, as was done in this study, aims to make the model accessible and understandable regardless of technical knowledge or experience (Özesmi & Özesmi, 2004). This means that it can be inclusive of a broader set of stakeholders than just the "technical experts" – offering a more holistic overview and potentially avoiding bias towards only technical or engineering solutions. The qualitative network provided a structure for discussion on the topic of heatwaves in a descriptive manner using existing knowledge and experience. Feedback from multiple stakeholders was that it was good to hear how people make connections between variables, that the visual representation makes it easier to digest and through seeing it, experts felt they could see gaps in knowledge and identify relationships. The adaptation lead believed that the exercise and time required to explore the determinants and influences of heatwave risk and resilience was beneficial to think about the situation systemically.

Wicked problems, such as adaptation, necessitate an approach that involves collaborative and social learning (Weber & Khademian, 2008). Findings from the study indicate that a participatory modelling approach may aid improved understanding of climate hazards, supporting the findings of Sanò et al. (2014). Stakeholder engagement to aid decision-making has real world benefits by seeing multiple interpretations of reality and bringing together beliefs, knowledge and perspectives (Voinov & Bousquet, 2010). It is suggested by Druzdzel (1996) that learning and insight gained via interaction to develop a network can sometimes be more useful than the output or recommendation of the decision support.

The findings therefore suggest that QPN is a time efficient, transparent, and collaborative method to identify and appraise adaptation actions at a high-level. This thesis argues that QPNs and the opportunities they offer for inclusion, representation, structuring and exploration of stakeholder knowledge for co-production and evaluation of adaptation options is a necessary step for effective and appropriate adaptation decision-making. This method appears a suitable first-pass assessment process, which can be supplemented by further evaluation (via CBA, CEA etc.) There were, however, also limitations of the QPN approach identified such as lack of precision, challenges in validation and facilitation support required. I modified the process to develop the QPN to minimise elicitation burden on stakeholders. Therefore, a full QPN was not created with stakeholders. Further research on effective techniques to engage stakeholders in eliciting and using probabilistic information (for QPNs) would be beneficial.

The approach used in the study explored how QPNs could support decision-making to build resilience to heatwaves. Findings indicated that the usefulness of QPNs would be improved when they are used in a situation where there is a clear adaptation vision, explicit objectives, robust evidence base, diverse stakeholders, appropriate resourcing, supportive organisational culture, engaged leaders, long-term thinking and an environment that is flexible and open to taking risks and embraces collaboration. Recommendations if the process were to be repeated include having a wide breadth of backgrounds and expertise of stakeholders contributing to network development and to have more time for detailed discussions on the reasoning behind identified influences and synergies within the QPN.  I argue that only within these settings can the process of QPN development be appreciated, and the outputs used in practice.

## 9.5 Conclusion

This research indicates that QPNs offer promise with regards to application in the field of climate adaptation at the city level. QPNs provide a mechanism to capture knowledge of decision makers and support collective discussion on the effects of alternative actions. Even in early development stages, QPNs can illustrate the effects of actions on variables. In relation to novelty or contribution of knowledge, it is the first time that QPNs have been developed in the context of climate adaptation (to the author's knowledge). Therefore, the QPN process and outputs presented in this chapter are suggested as illustrative pilots. The application of QPNs further to climate adaptation, would need refining.

Findings also suggest that QPNs can be useful initial steps before committing to the development of a BBN, if the problem situation requires more precision. QPNs can offer a first pass version to inform quantitative probabilistic networks (Bayes Fusion LLC, 2020b). This qualitative approach of QPNs provides a way to structure ambiguous and diverse knowledge into a network which can be used to inform more advanced quantitative methods, such as BBNs. The following chapter compares the findings from both the BBN and QPN study.

# Chapter 10: Comparative study of BBN and QPN studies and proposed protocol to support method selection

> "With many decision-making processes available…the question for adaptation decision-makers becomes how to choose a decision-making process."
>
> (Siders and Pierce, 2021, p.4)

Climate adaptation decision-making is complex (Head, 2014). The ability to make adaptation decisions is influenced by the context in which decisions are made and the content available for consideration as well as the process used to inform options appraisal (as evidenced in Chapter 6). Whilst there are a wide range of decision support methods available, different methods will be more or less applicable depending on the problem context, data availability and decision-maker. As climate change adaptation decision-making is important for the future of our society, natural and built environment, it is imperative that suitable support methods are identified and utilised in the appropriate settings.

As such, this thesis explored, through action research, the appropriateness of BBNs and QPNs. Chapters 8 and 9 assessed each method separately. This chapter discusses the commonalities and differences between the two approaches in relation to the context, content and process challenges identified, using the CCP framework (introduced in Section 6.3).

This chapter therefore addresses research Objective 2 which was to assess the value of Bayesian Belief Networks (BBNs) and adjusted Qualitative Probabilistic Networks (QPNs) as methods to support climate adaptation decision-making within a city council and address challenges identified via Objective 1. Value is defined within this thesis as the usability and usefulness of the method and the resulting benefit of the process and/or output to decision-making. Value is assessed in relation to the identified challenges in the decision-making context, as well as the content (data and information) required, and process undertaken.

The comparative assessment is achieved through evaluation of multiple data sources. Data was collected via feedback from developers and users of the networks. For the BBN, evaluation was undertaken through a semi-structured interview with the decision maker. For the QPN, participants took part in a feedback discussion at the end of workshops and completed a questionnaire which asked to what extent they agreed on provided statements on the usefulness of the QPN using a Likert scale (1-5) (Appendix XVI). In addition, observations from my role as a facilitator and action researcher in the development process are offered.

This chapter is structured as follows. The findings from Chapters 8 and 9 exploring the application of BBNs and QPNs to climate adaptation are compared using the CCP framework against context (Section 10.1), content (Section 10.2), process (Section 10.3) and then a holistic overview across all three elements is offered (Section 10.4). This leads to identification for the need for further guidance (Section 10.5), the proposal of a protocol process to assess when BBNs or QPNs are appropriate for other adaptation problem settings (Section 10.6). A summary of the chapter is then offered (Section 10.7).

## 10.1 Context: comparing BBN and QPN

Section 6.4.1 highlighted challenges arising from the context in which adaptation decision-making was occurring. The context was defined by lack of resource, in relation to time, staff, funding and technical skills. It was thus observed that hypervigilant decision-making was occurring, caused at least in part by the perception that there was not sufficient time or resource for a thorough decision-making process. Local authorities in Scotland (and the UK and Europe) are facing further resource constraints and limited budgets because of austerity and the COVID-19 pandemic. It is thus crucial to consider the resources required by different decision support approaches, to assess their applicability to the local context. Thus, this section seeks

to explore to what extent BBNs and QPNs are useful in this context considering (i) resource requirements (time and funding) and (ii) technical skill availability.
Time and financial resource availability can limit the uptake of decision support methods. Many existing elicitation protocols including IDEA and SHELF (O'Hagan, 2019) assume that experts can contribute a significant amount of time to network development, which as Chapter 6 demonstrated, is often not the case for climate adaptation in local authorities. In relation to the BBN, it was found that stakeholders felt the resource commitment was high (in terms of time and cognition). The time requirements needed from experts to be able to provide conditional probability estimates to populate the CPTs was least two hours each on average, just to populate components of the BBN. The challenges associated with time required to elicit CPT values for a large network have been noted by Coup and Gaag (1998) and Cain (2001). Time constraints led to a limited number of states for each node being introduced to minimise time needed for the elicitation process, which in turn affects network detail. The QPN similarly had relatively high time requirements as the network was developed over two full day workshops, however had less elicitation burden because of the qualitative structure.

In terms of technical skills required, the BBN required quantitative estimations of CPTs whereas the QPN only needed qualitative estimations of the strength of influence and synergies between nodes in the network from stakeholders (Cain, 2001; Wellman, 1990). Stakeholders involved in the BBN creation reported that they found the elicitation process mentally taxing and tiring and were not always comfortable providing probability estimates. The QPN, however, did not require excessive skill or mathematical ability from stakeholders. An identified advantage of QPNs therefore is that they are potentially more accessible and understandable to a wider set of participants regardless of technical background.

The ability of an expert to participate in elicitation may also be dependent on previous experience and/or training. Power et al. (2018) highlight how high staff turnover or reallocations, often driven by budgetary limitations and the natural working cycles of the civil service, can result in staff working on climate change who do not possess formal training or experience on climate change, climate adaptation and climate related decision-making practices, serving as a barrier to effective documentation and use of required information for decision-making. Training may however provide knowledge and skills development. For instance, Gigerenzer et al. (2007) trained medical doctors in use of Bayes' rule and advocated for training for practitioners in other fields in statistical inference. Challenges though include the costs of training and lack of data on efficacy in practice (Dhami et al., 2019). I suggest that training of adaptation practitioners may enhance competence and confidence in using decision support methods and ultimately making adaptation decisions. The network development for both BBN and QPNs however would need to be owned or lead by someone with the ability to transfer the networks developed in workshops to a computerised version and perform analysis accordingly. In terms of financial resource, software for BBNs and QPNs are available freely.

In summary for contextual challenges, the BBN approach was found to require high technical ability of stakeholders including the understanding and use of probabilities. In addition, the time commitment needed for expert elicitation was relatively high. As a result, I suggest a BBN method may not be appropriate for the study context, given the limited time and personnel available for adaptation work. This could be addressed with additional training if resource (financial and time) was available in the future. QPNs appear to be a viable preliminary method, that is feasible within the context setting. This is because QPNs are useful in situations where there are no quantified probabilities available and or when there is not time available to elicit or collect them (Devilee & Knol, 2011).

## 10.2 Content: Comparing BBN and QPN

Challenges faced by practitioners arising from the content, or information used in decision-making, outlined in Section 6.4.2, included that local data is not always available or there may be knowledge or data gaps. Furthermore, data may not be in an accessible format or up to date, nor the decision maker able to use the information effectively. This thesis found that limited evidence on the climate risks resulted in vague and incomplete identification of proposed actions and made the decision-making process difficult. Adaptation generally may be challenged by partial knowledge and uncertainties as quantitative data relating to climate risks and adaptation options is often not readily available, or the cost is prohibitive to use (Kiem et al., 2014; Williams, 2012). One way to procure, identify and collate information needed for adaptation decision-making is through expert elicitation (Doria et al., 2009).

Both the BBN and QPN approach used expert elicitation to help address content or knowledge gaps. The usefulness of the methods to address the content challenges was assessed against criteria including information availability, precision, and validation. Finding from the BBN and QPN studies with regards to these categories are summarised in Table 10.1 and presented here. Firstly, the content (data and evidence), both available and required for decision-making, will affect if BBNs or QPNs are useful. In relation to information availability, both studies were challenged by lack of information on the causal relationships between determinants of climate resilience. Hence the ability of both methods to utilise expert elicitation was beneficial.

The produced BBN integrated quantitative information (properties or people at risk), as well as qualitative information (extent of adaptive capacity), which was found to be advantageous. Through integration of data sources, BBNs can derive probability distributions between variables, which reduces limitations imposed by lack of data (Catenacci & Giupponi, 2009). The ability for BBNs to integrate information which can be iterated over time as more information becomes available (whilst not employed within this study) is seen as advantageous for the rapidly evolving climate adaptation field (Pollino & Henderson, 2010).

The QPN, however, may be seen as less strong in addressing existing knowledge and data gaps, despite being able to integrate data, because the precision was less. In a qualitative probabilistic network, as opposed to a quantitative probabilistic network which is a BBN, the precision is reduced to signs which can be used to explore significance of evidence on variables (Druzdel, 1996). QPNs differs from BBNs in that it contains qualitative probabilistic relationships by showing how the values of one nodes influences the probabilities of the values of the other (as opposed to providing conditional probabilities) (Renooij & Gaag, 1998).

Different levels of precision are thus offered by the different decision support methods. There may be a trade-off between the robustness of detail and the understandability and accessibility of the network. BBNs are seen as mathematically and statistically rigorous and as such there may be an assumption that given, they are numerical method, BBNs require exact numbers and high accuracy (Biedermann & Taroni, 2006). Accurate numerical data, however, is not always a requirement. QPNs model the probabilistic relationships between variables at a higher abstraction level than BBNs (Bolt et al., 2005). Therefore, reasoning in a QPN may not be as informative as a BBN. This was evident in the deeper level of option analysis offered by the BBN (Section 8.3) in comparison to the QPN (Section 9.3). This research did illustrate the relative importance of the qualitative structure of the network, in other words the graphical representation of dependencies, in favour of precision in numerical estimates.

Research has shown that full precision in probabilistic relationships (for example in a BBN) is rarely required to make a decision and in many cases qualitative information (such as a QPN) is sufficient (Goldszmidt, 1994). For instance, Wilby and Dessai (2009, p.182) state “Even qualitative descriptions of climate variability or the direction of change can help planners embrace uncertainty by looking for more resilient options that meet agreed standards”. Climate change adaptation decision-making is often underpinned or informed by quantitative risk assessments. Qualitative information, in comparison can be perceived as incomplete understanding, messy, uncertain, and less valuable than quantitative data. There is however, limited knowledge on which problem settings and tasks require what level of precision as the level of detail required will be context dependent (Liu & Wellman, 1994).

The aim of creating a QPN was to explore the trade-off between expert input and confidence with granularity of analysis. QPNs model influences at a coarse level, capturing if the influences are either positive, negative, zero or ambiguous, whereas the BBN provided more detailed analysis. The QPN approach was studied to see how different input resource affected the value of the output. On the basis of this study, I believe that QPNs can be useful as they are for rapid creation of simplified causal models. QPNs are therefore useful for strategic problems which are complex enough to require decision support and are also too complex to be represented by fully specified, precise quantitative models. If the level of precision needed is greater and the context is appropriate (resources available in terms of time and knowledgeable experts), than a BBN can provide insight on the performance of options and combinations of action, as well as assisting in ‘what if’ testing to consider how options perform under different futures.

In summary, for addressing content challenges, this thesis argues that expert elicitation has an important role to play in climate adaptation decision-making due to the ability to aid decision-making in a transparent manner (Thompson et al., 2016). BBNs and QPNs both offer ways to engage stakeholders to identify and address content or data gaps. I suggest that BBNs are stronger in terms of their ability to integrate quantitative and qualitative data and easily be updated over time.

### 10.3 Process: Comparing BBN and QPN

In relation to process, Section 6.4.3 identified several specific challenges arising from decision-making process including (i) lack of problem diagnosis and understanding and (ii) lack of thorough consideration of alternative options via options identification and appraisal process. The BBN and QPN’s ability to aid system understanding through identifying determinants of resilience and the extent to which the methods illustrated the effect of proposed adaptation actions and assess the co-benefits of adaptation actions to inform decision-making, was studied. Results are summarised in Table 10.1 and described below.

In terms of improved problem understanding and problem diagnosis, both the BBN and QPN offered the ability to formalise and structure knowledge, acting as a heuristic[50] to explore information relating to the decision problem and enhance understanding of actors. The BBN helped illustrate key components and relationships within the problem context. This strength was noted by the decision maker during a

[50] Heuristics are useful for complex situations to aid decision-making that are not linear or clear which option is most effective. The topic of heuristics is gaining traction within climate adaptation. Heuristics are rules that guide decisions and can provide mental shortcuts. Nalau et al. (2021) highlight that it is important to explore what practitioners know about heuristics and how they are used, pointing out that little is written on this topic in climate adaptation context.

conversational interview, commenting that seeing the visualisation helped understand the context of flood risk in Glasgow. This finding confirms, the advantage cited in the literature, that BBNs can help understand a problem situation by breaking down complex causal chains into components which can be examined separately (Catenacci and Giuponni, 2008). There are other methods available for visualising systems, including concept maps, cognitive maps and mind maps which are graphical representations of interlinkages. Whilst the simpler methods such as cognitive maps can help show causal relationships, climate adaptation requires methods which can handle complexity and uncertainty and thus requires a more formal approach. This is where the BBN and QPN strength lies.

The QPN was also found, via workshop feedback, to aid problem diagnosis and understanding (stakeholders gave it an average score of 4.5 out of 5 for this characteristic on the evaluation survey). Respondents indicated the QPN supported knowledge exchange and consensus building as it provided a medium to bring stakeholders from different backgrounds together and combine their knowledge to build a rich picture of the problem setting. A strength of the QPN study was the participatory nature of the approach. For example, during the feedback session at the end of the QPN workshops, attendees commented that being able to hear and see the input from others with different backgrounds was useful for improving their own understanding of heat risk and resilience.

Research highlights the importance of participatory methods. For the BBN approach, each expert elicited discrete sections of the BBN and the GCC decision maker reviewed the collated BBN; therefore, there was no need for aggregation. This methodological choice was due to expert availability and the finding from previous action research undertaken in the thesis (Chapter 6) that expert was far more frank, open, and reflective in one-on-one situations rather than in group discussions where often one person dominates or influences. The QPN study however was predicated on the need to bring stakeholders together to 'own' the model. As such aggregation was an aspect of research design and implementation via consensus. I argue that a participatory method which enables aggregation by consensus was advantageous for encouraging detailed discussions, exchanging knowledge, and reaching agreement across the group. This approach could be adopted within either a BBN or QPN methodology. Reflexive learning is central to developing knowledge, learning and confidence related to adaptation planning (Fünfgeld et al., 2019). Fünfgeld et al. (2019) found that decision support methods can aid collaboration and capacity building.

Learning from both studies highlights the benefits of stakeholder participation in network development. Whilst good practice BBN development guidelines stress the need for stakeholder involvement during all steps of the network development, Sperotto et al. (2017) reviewed published BBN studies relevant to climate adaptation and found that very few case studies actually involved stakeholders throughout the process. The process of stakeholder engagement during QPN development was observed to offer greater value than the outputs in this respect. The ability to capture insights from diverse stakeholders important for decisions that must be cognisant of the local context, which is the case in adaptation (Moallemi et al., 2020). As evidenced by Chapter 6, good or improved scientific information, however, may not be enough to result in improved decisions as there are wider factors at play including values, social dynamics, competing risks. Therefore the ‘softer’ benefits of BBNs and QPNs (such as learning and transparency) may be greater than their ‘hard’ benefits (such as the completed networks and mathematical evaluation of options) as was the case in this study. To this end participatory approaches can support the understanding, implementation and improvement of resources to support decision-making (Fünfgeld et al., 2019).

In terms of supporting options identification and assessment to inform decision-making, the developed networks can provide a common basis of shared knowledge to support discussion and appraisal of options (Giupponi et al., 2011). A strength of BBNs and QPNs is that they help identify changes, as a result of interventions, but also helps users understand why changes are occurring. The networks help identify clear actions based on understanding of how the system works as a whole. Participant feedback revealed that the QPN process was scored an average of 4.25 (out of 5) in relation to ability to inform decision-making. Whilst the BBN process did aid options appraisal, the decision maker reflected that it was difficult to provide quantitative estimates of the effectiveness of adaptation actions (in terms of enhancing flood resilience). There is a risk that the simplistic visual representation of a BBN or QPN, provided to users masks the probabilistic equations underlying them (Založnik et al., 2021). This can help make them more accessible to users but also means there is not a full understanding of their deeper meaning and overconfidence in the results (Richards et al., 2013).

BBN and QPN methods support consideration of hypothetical causal relations between events and one can explore alternative explanations of options, consider trade-offs and observe consequences of actions (Fenton and Neil, 2019). In addition, the application of BBNs and QPNs offers an alternative to spatial representations of vulnerability and resilience and instead focuses on the causality and relationships between factors which influence the resilience of the urban system. The ability to structure the problem and see how the proposed actions could contribute to the objective visually and numerically were beneficial.

The findings from this research in relation to decision-making process, suggests that in general BBNs and QPNs could serve as useful mechanisms to visualise and communicate perceived determinants of resilience and the varying effects of different adaptation options to local authority decision makers. Both the BBN and QPN helped understand the problem and thus evaluate options. It was identified, however, that the QPN process was more accessible to wider audience of stakeholders, without technical backgrounds, making the process more inclusive. To transition to vigilant decision-making, the process needs to enable a systematic and organised information search which underlies thorough consideration of all available alternatives. Thus, it is argued that both BBNs and QPNs may be useful approaches to support and enable vigilant decision-making in practice. A summary of how BBNs and QPNs respond to the context, content and process challenges specified in Chapter 6 is offered in Table 10.1.

Section 3.1 introduced the idea of an ‘adaptation journey’. The different stages of an organisation’s adaptation journey relate to progression in complexity of activities undertaken, competencies of staff and speed and extent of implementation. As such, alternative decision support methods may be best suited at differing stages of the adaptation journey.

Different decision support methods are better suited to different phases of the adaptation journey due to changing contexts as well as evolving capability and maturity. For instance, when an organisation is developing maturity (in terms of adaptation and generally), the level of knowledge increases, confidence in assessment increases, and stakeholders become more comfortable expressing opinion (Yeh et al., 2017). For instance, decision support methods with elicitation needs may be better suited to more advanced stages or more mature organisations. The elicitation process associated with decision support may be able to evolve from less to more challenging as organisations mature (French, 2020). As organisations mature, decision-makers may become more knowledgeable, desire more detail to inform decision-making and the challenging surrounding elicitation may have eased. Similarly, as an organisation matures, their willingness to commit to a decision support method that requires time may increase as they increasingly value the process and outputs associated with decision support.

Stafford Smith et al. (2022) introduced three archetype modes of the adaptation cycle as Scan, Portfolio and Project. The Scan phase could be designed in a way which establishes the foundation for appropriate and strong decision-making by identifying stakeholders, building buy in, identifying qualitative scenarios, initial risk identification. A QPN could therefore be suitable during the Scan mode for identifying initial qualitative influence relationships. However, the BBN would better suited to the Portfolio mode, given the need for willing participants, knowledge of scenarios and at this point, the practitioners have identified specific decisions and options. BBNs require more expertise from decision makers and the elicitation process is more challenging. This supports French (2020) suggestion that transitioning from qualitative to quantitative approaches aligns with enhancing complexity. For instance, a more experienced or knowledgeable decision maker may have more competence and skills to make decisions as they may be able to recollect similar situations, apply learning to identify innovative options for adaptation and effectively scan for relevant opportunities. The decision support methods used and the elicitation techniques employed within this research where cognisant of the maturity of the individuals and the organisation being engaged.

*Table 10.1: Comparison of the BBN and QPN approaches used in this thesis in terms of ability to address CCP Factors*

| | **Factor/Consideration** | **BBN** | **QPN** |
|---|---|---|---|
| Context | Resource - Time | Time intensive | Relatively time intensive |
| | Skills & Technical Knowledge | Requires understanding of probability, associated with elicitation burden | No training or quantitative ability required (for adjusted QPN approach used) |
| Content | Data use/information availability | Can integrate multiple sources of data (including qualitative and quantitative) | Qualitative data – limited integration |
| | Elicitation Burden | High – requires time and technical skills | Low – no technical skills or numerical background required, and can be done in relatively short time period |
| | Aggregation | N/A Each network component quantified by separate expert | Via conversation – found to be helpful for knowledge exchange and consensus building |
| | Validation | Can validate against existing data | Less precise representation of system, difficulty in validating |
| Process | Ability to identify factors which contribute to or enhance climate resilience | Adaptation lead outlined that BBN helped identify what actions would be helpful or not to do. It was stated that information on quantifiable effect of actions aided decision makers to look for options which maximised ability to achieve objective | Through feedback, workshop participants said approach was very useful and they liked the visual element of output. Noted benefits included that the approach allowed the group to isolate and understand factors and relationships.<br><br>Within evaluation questionnaire, participants provided score 4.5 out of 5. |
| | Illustrate potential of proposed adaptation actions | Stakeholders were not comfortable giving probabilities about the potential effect of adaptation actions. This was because the actions were felt as too ‘woolly’ in that there were not well defined. Thinking through how action would affect nodes in BBN, however, can help refine actions to be more specific. | Participants response to this aim was ‘Yes definitely’. It helped provide a good understanding of the proposed actions and how other stakeholders viewed them.<br><br>A 4 out of 5 score average via questionnaires. |
| | Evaluating co-benefits of adaptation actions | Numerical estimates of benefits of taking actions together was seen as useful but there was a desire for further insight on co-benefits of actions (however decision maker acknowledged need to further develop options to enable this) | Feedback was that it was easy to understand the co-benefits between actions through visual assessment of QPN, however was lacking detail.<br><br>This element received average 3.75 out of 5 score. |
| | Inform decision-making | Decision maker stated, “Today’s interview was helpful to think about detail, wording and impact of actions and I would use as a tool like to appraise options – maybe a good method to engage colleagues. At GCC we have vision but don’t consider how actions will help us achieve this vision. The BBN helped change thinking and having an external person query helps me consider actions, appropriateness of strategy.” | Whilst participants said they found the QPN to be useful to unpack adaptation actions, it was noted that some uncertainties remain especially when it comes to the long timescales.<br><br>Score received was 4.25 out of 5. |

### 10.4 Summary of BBN and QPN assessment

The previous section (10.3) explored how BBNs and QPNs address context, content, and process challenges individually. This section now explores their usefulness holistically in relation to all CCP factors. From my perspective as a facilitator both approaches were beneficial in that they involved stakeholders, however differed in the level of engagement and amount of technical skill required. From the point of view of the decision maker both methods aided understanding of the problem. The QPN approach, however, did influence the development of GCC's climate adaptation plan by identifying actions for heat resilience, which otherwise wouldn't have been included. Lastly, considering the approaches as an analyst (also from my perspective), the BBN provided greater analysis and quantification of effectiveness of options in comparison to the QPN.

In summary, within this research, the BBN approach was observed to: (i) have relatively high time requirements for expert elicitation; (ii) generate significant elicitation burden on the experts consulted; (iii) highlighted people's discomfort in speaking in the form of probabilities and the difficulties in quantifying aspects of the model which are not able to be seen or studied in practice yet; and (iv) be unhelpful when conducting elicitations with experts individually in isolation in terms of promoting knowledge sharing. Results did highlight that creating the qualitative network structure, including identifying relevant variables and mapping out causal relationship between them was seen as valuable to the decision maker to aid understanding of the system. Findings from this study suggest that the QPN approach (in this research) was more effective than the BBN for building understanding and bringing stakeholders together. An advantage of the QPN, may be the increased richness in qualitative network detail given the reduced quantification burden. Limitations, however, include the subjectivity of assumptions and lack of precision.

It is evident that given the gravity of climate adaptation, decisions should be made on robust, technical information that appreciates the complexity of the problem. However, decision makers or users will need information in accessible format and/or support in using it. Whilst objectively it is easy to argue for such robustness, the reality is decision makers, particularly in local authorities, are challenged by lack of resource. There needs to be a balance between accessible information and resources and technically robust approaches. This chasm may be addressed via engagement activities and exploration of trade-offs. This research also found that the decision maker(s) is key and that characteristics of the individual can heavily influence the options appraisal process and outcomes. Processes can be negatively affected by (perceived) lack of confidence or competence of decision maker(s). BBNs and QPNs, therefore, may be best suited to aid adaptation, in circumstances where the antecedent conditions are appropriate. By this, I mean that the context in which the decision is being made, including resource availability and the content under consideration, all influence to what extent expert elicitation may help.

Based on the findings, this thesis argues that there is a need for decision support processes for climate adaptation that are easy to understand, accessible to local authority stakeholders, able to combine diverse information, can be applied with very limited time and resource with transparent and usable outputs. These contextual considerations need to be made alongside considerations of what content is being assessed. The following section (10.5) combines these findings to propose a generalisable process to ascertain when and if a BBN or QPN approach would be helpful to aid climate adaptation decision-making.

### 10.5 Protocol for assessing applicability of BBN and QPN

Climate change adaptation decision-making can be aided by decision support methods. The past two chapters (8 and 9) presented the application of two approaches to support adaptation decision-making, BBN and QPN, respectively. Section 10.1-10.4 reviewed the approaches in relation to the CCP factors identified in Chapter 6 and demonstrated that selection, use and effectiveness of decision support is highly dependent on the decision setting, including the context, content, and process.

Options identification and appraisal is a common component of many adaptation guidance resources (as discussed in Section 3.1). There is, however, an identified need for research to explore which adaptation tools and strategies should be used in different problem settings (Siders & Pierce, 2021). This thesis demonstrated the value offered by the application of BBN and QPNs such as addressing data gaps via expert elicitation and helping strengthen understanding of the system through visual causal mapping. However, it is important to understand under which conditions they should be applied. As such, the remainder of this chapter addresses this knowledge gap by reflecting on the conditions suitable for BBNs and QPNs to propose a protocol to assist identification of when these approaches are suited for other climate adaptation decision-making situations (both research and practice).

There is an emerging subset of academic literature exploring the appropriateness of different decision support tools within the climate adaptation field. Published studies of common methodological choices in decision support frameworks for climate adaptation include Dittrich et al. (2016), Maier et al. (2016), Herman et al. (2015) and Kwakkel and Haasnoot (2019). Shi et al. (2019) for example, developed a six-step screening procedure to inform analysis for adaptation decision-making focusing on predict-then-act analysis and multi-scenario analysis, whilst considering the effect of adaptive options. Whilst existing decision support selection frameworks are beneficial in that they enable consideration of appropriate methods for different contexts, they remain limited for three reasons.

Firstly, none specifically reference probabilistic network methods, such as BBNs and QPNs, yet this thesis demonstrated the value of such methods under certain situations. The benefits of BBNs, in particular, to climate adaptation are increasingly being cited in the literature (Catenacci & Giupponi, 2010; Maskrey et al., 2016; Richards et al., 2013; Sperotto et al., 2017). As such, there is a need for a protocol to help practitioners and researchers identify which circumstances they may be used. Similarly, there are no published studies using QPNs in the field of climate adaptation, despite their advantages. The protocol thus helps highlight when they may be applied.

Secondly, Moallemi et al. (2020) highlight that common protocols do not examine how researchers and practitioners should make choices that are most appropriate in different levels of knowledge, are not aware of the factors that influence methodological choices and do not often explore consequences of choices on outcomes. As such, the produced frameworks and screening processes, to date, are complex and have a burden associated with using them. Whereas the following protocol attempts to address this limitation by reducing this burden by making it a very simple, easy to understand process.

Finally, Siders and Pierce (2021) found that although a wide range of decision-making strategies have been developed, they are rarely used to make climate change related decisions. Palutikof et al. (2019) also stress that decision support resources are required for practitioners to be able to select appropriate adaptation responses, that are commensurate with the current and growing adaptation challenge. This thesis demonstrated lack of decision support methods is influenced by limited resource, time, and lack of awareness of which methods exist and are most appropriate. The protocol aims to address by accounting for the context with which the decision-making is set in thereby aiding selection of appropriate support. Fünfgeld et al. (2019, p.628) state, “the choice and use of a decision-support tool needs explicit cognisance of organisational culture, routines, norms, politics, and resource capacities because these dimensions can all affect its use and efficacy in contributing to organisational adaptive capacity. Organisations may have difficulty in understanding which support method to use, given the vast amount and diversity of options”.

The aim of the proposed protocol is to support researchers and decision makers in identifying when BBN and QPN support may be applicable during options identification and appraisal process within the adaptation decision-making cycle. The protocol draws on the CCP to help the decision maker appropriately evaluate how contextual factors and content availability affect the decision support processes and ultimately decision support tool selection. The protocol thus is informed by learnings from Chapters 6, 8 and 9 and highlights the transferable learnings from the GCC study. The proposed protocol aims to enable vigilant decision-making thorough canvassing of available options and considered assessment (Keinan et al., 1987).

Whilst this research conducted an in-depth study of GCC, it is argued that there are many learnings pertinent for other organisations making climate adaptation decisions. Findings were validated via two interviews with practitioners in Northern Ireland and the Netherlands (as described in Section 6.4.5). Northern Irish and Dutch adaptation contexts differ in terms of policy environment and resource availability. As such, the protocol was shared with them to get feedback from different perspectives.

The intended audience for this proposed protocol, are practitioners and researchers involved in city level climate adaptation. The screening process can be used by city council sustainability or climate officers to assess in which circumstances BBNs and QPNs may be useful. Similarly, the protocol may be suitable for researchers assessing if BBNs or QPNs are appropriate research methods for their research setting.

## 10.6 Protocol structure

This thesis proposes a protocol using a flow chart process that helps the decision maker consider different key questions relating to CCP factors. The protocol supports users to understand what course of action is required. The themes considered in the protocol are: (i) awareness and recognition of climate risks to the organisation; (ii) resource in terms of time and finance; (iii) data availability; (iv.) stakeholder availability; (v.) stakeholder numeracy and (vi.) level of precision required from decision support (as outlined in Figure 10.1). Appendix XVII provides detail on the description of each section, the prompt questions users should consider and defines potential responses. The protocol also poses questions to explore the context and content related to adaptation decision-making. Consideration of these elements are useful, irrespective of whether BBN or QPNs are ultimately selected, as it will help aid understanding and improve the decision-making process.

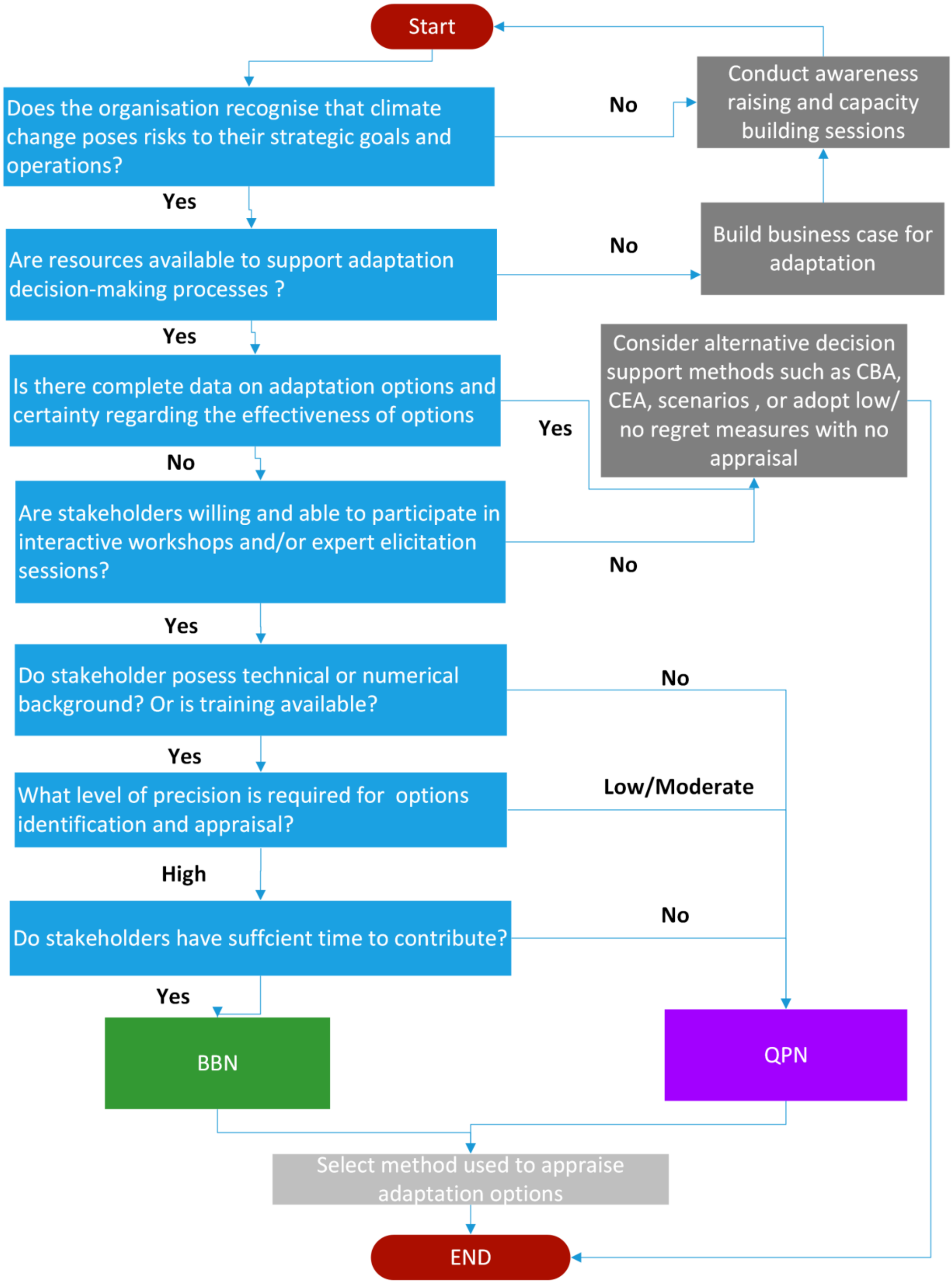



*Figure 10.1: Simple protocol for assessing if application of BBN or QPN is appropriate given organisational setting and characteristics*

The protocol was tested by adaptation practitioners in Northern Ireland and the Netherlands. The questions were posed to practitioners and their responses used to guide the trajectory via the protocol. Both validation interviews using the protocol indicated that QPNs may be the more appropriate method to use in their settings. This was due to limitations in both contexts. The responses of interviewees to protocol prompts are available in Appendix XIX. Both interviewees indicated that there was a need for a protocol and that this would make a contribution to practice. Both respondents indicated the dearth in options appraisal methods used (by them) may be due to the early stage /embryonic nature of adaptation. In their experiences, actions being proposed currently relate to collecting information, developing databases as opposed to significant on the ground delivery.

The need for enhanced insight on how to appraise actions was identified by both practitioners. For instance, the Dutch stakeholder said at the moment there is no specified guidance or method for selecting adaptation options. The interviewee stated, “There's not really a method for deciding what action to choose, and I think a method would be helpful for that.” The Northern Irish stakeholder similarly felt that a method to help identify and appraise options was needed as local authorities mature and progress their adaptation work in Northern Ireland. It was also commented by the Northern Irish interviewee that it is anticipated that an influx of private sector offerings for adaptation will occur in the near future and if local authorities were either able to undertake options appraisal themselves or assess which method, they would like a consultant to help with, that would be beneficial. It was suggested that having a standard approach which numerous councils use, would be helped by the provision of such a protocol.

## 10.7 Conclusion

The task to identify adaptation actions is a standard activity in almost all adaptation guidance and frameworks, however, there remains limited knowledge on what methods city councils would benefit from and importantly which they can use themselves. Through action research, it was possible to develop and test a BBN and QPN in real-life setting with actual adaptation decision makers and practitioners. This chapter summarised 'proof of concept'[51] examples of how BBN and QPN approaches have the potential to support adaptation decision-making. To the author's knowledge, this is the first study to explore the use of QPN in illustrating relationship between perceived determinants of climate resilience and to attempt to quantify the potential changes in climate resilience as a result of varying interventions.

This chapter assessed the findings from the development of a BBN and QPN for climate resilience in relation to the context, content and process challenges for adaptation decision-making, identified in Chapter 6. The advantages of both methods to aid decision-making were highlighted, including addressing knowledge gaps, integrating qualitative and quantitative information, building system understanding and illustrating the effects of different interventions. I argued, however, that the effective use of a BBN or QPN will depend on the setting in which the methods are being applied. As such, a protocol was developed to support practitioners and researchers in assessing when a BBN or QPN may be useful for climate adaptation decision-making. This thesis argues that more structured decision-making processes which take account of context and content and incorporate local knowledge and enable vigilant decisions making processes are needed to achieve effective climate adaptation in cities. The following and final chapter (11) concludes this thesis by recapping on the identified research objectives and explaining how they have each been met.

[51] As stated in the research aim and objectives, this thesis sought to assess the value of BBNs and QPNs to climate adaptation decision-making. Thus, this research was just initial step to determine the feasibility of the methods to the setting of adaptation. Further additional, detailed research would be required to develop the applications to a sufficient standard for widespread use.

# Chapter 11: Conclusions and Recommendations

Climate change poses an existential threat to the wellbeing and viability of global ecosystems, livelihoods and localities (C40 Cities & UCCRN, 2018; IPCC, 2018; Met Office, 2019). Adaptation however, if done correctly, offers an opportunity to not only mitigate such risks but positively contribute to more just and prosperous places (Meerow & Stults, 2016; Satterthwaite & Dodman, 2013). The decisions that underpin adaptation planning are thus of significant importance. Cities as the loci of a growing share of the world's population and city councils as the providers of essential services, are key actors in addressing the impacts of climate change (Hunt & Watkiss, 2011b). Climate adaptation and resilience have thus become common goals city councils must work towards (Rosenzweig et al., 2010).

Climate adaptation decision-making at the city council level, however, is challenged by knowledge gaps. There is limited knowledge of how adaptation theory and guidance is translated into practice (Lourenço et al., 2014; Patwardhan et al., 2009). It is also recognised that there are a number of barriers restricting adaptation (Biesbroek et al., 2011; Ekstrom & Moser 2014; Moser & Ekstrom 2010b), but less about how these challenges occur and interact with each other (Oberlack, 2017). In addition, there are influences affecting which decision support methods are most appropriate for climate adaptation (Siders & Pierce, 2021). Whilst the benefits of BBNs to addressing these climate adaptation challenges have been cited in the literature (Catenacci & Giupponi 2010; Sperotto et al., 2017), there has been limited application to date (Maskrey et al., 2016; Richards et al., 2013) and further study is needed.

The aim of this thesis was to analyse climate adaptation decision-making in Glasgow, Scotland guided by the following research question: What influences challenge climate adaptation decision-making currently and what is the value of using alternative decision support methods? To do this, action research studying decision-making in practice with a case study of Glasgow City Council was undertaken during the development of two strategies: the Glasgow Resilience Strategy and Climate Adaptation Strategy and action plan. Influences on adaptation decision-making arising from the content, content and process were identified. Subsequently, two different approaches to address the decision-making limitations (Bayesian Belief Networks and Qualitative Probabilistic Networks) were trialled. The empirical results of the BBN and QPN studies were combined with qualitative data on their value collected from observations, surveys, and interviews with relevant stakeholders. The mixed methods approach allowed a comparison between the two approaches with regards to their advantages and disadvantages and their value in aiding city-level adaptation decision-making.

In the remainder of this chapter, a summary of the thesis objectives and methodologies are presented (Section 11.1). The key conceptual, methodological, and empirical findings and contributions of the thesis are then presented (Section 11.2). Following this, Section 11.3 sets out recommendations for future practice and areas for future research. Finally, Section 11.4 presents concluding remarks on the key findings and questions arising from this thesis.

## 11.1 Research objectives and methodologies

This section provides a brief summary of the thesis objectives and the respective methodologies employed to achieve them.

### 11.1.1 Overview of Objective One

The goal of Research Objective One was to identify the challenges influencing current adaptation decision-making within the real-world context of a city council developing an adaptation strategy and action plan. To achieve this objective, action research was undertaken with Glasgow City Council studying the development of Glasgow's Resilience Strategy and the ongoing Glasgow Climate Adaptation Strategy and Action

Plan. A mixture of participant observation, facilitation and semi-structured interviews were used to collect relevant data.

To study the development and decision-making processes of the resilience and climate adaptation strategies, a total of 200 hours of data collection was undertaken between September 2015 and February 2020. This involved: (i) attending, observing and/or facilitating eight task group meetings and 12 workshops; (ii) conducting 27 semi-structured interviews with 38 stakeholders and collecting data via (iii) two questionnaires and (iv) completing a Local Climate Impacts Profile (LCLIP) for Glasgow. Additional semi-structured interviews with adaptation practitioners in Northern Ireland and the Netherlands validated the emerging findings, highlighting the transferability of the thesis arguments.

### 11.1.2 Overview of Objective Two

The goal of Objective Two was to assess the value of Bayesian Belief Networks (BBNs) and adjusted Qualitative Probabilistic Networks (QPNs) as decision-making methods to support climate adaptation decision-making within a city council and address challenges identified via Objective One. Value was defined within this thesis as the usability and usefulness of the method and the resulting benefit of the process and/or output to decision-making. Value is assessed in relation to the identified challenges in the decision-making context, as well as the content (data and information) required, and process undertaken. Data (including network structure, numerical estimates of conditional probability tables (CPT)s, oral and written feedback on network development) was collected via five workshops, four expert elicitation sessions and two questionnaires. Findings were used to inform the development of a decision-making protocol to enable decision makers and researchers to consider when BBN or QPN application may be appropriate to use.

This thesis focused specifically on the case study of GCC for both research objectives to allow for in depth and granular evaluation of the various factors affecting day to day decision-making which would not be picked up from a more lighter touch case study. Such depth of evaluation presented new findings and valuable contribution to knowledge in terms of identified context, content, and process influences. The methodology employed was found to be effective due to the unique embeddedness of the researcher (being an adaptation practitioner in the region) as well as the facilitation skills held by the researcher which enabled unique access to observe the intricacies of decision-making process which tends to occur behind closed doors and is out of reach of most methodological processes.

## 11.2 Conceptual contributions

Through undertaking research to address research Objectives One and Two, three claims are made. These include that: (i) influences challenging adaptation arise from the context, content and process, the interlinkages of which must be examined holistically; (ii) current risk-based, rational models of adaptation decision-making such as the Adaptation Wizard do not adequately consider the influences facing city-level adaptation thus leading to hypervigilance; and (iii) BBNs and QPNs offer value in appraising adaptation options and supporting a transition to vigilant decision-making. This section presents each conceptual contribution individually.

### 11.2.1 Adaptation decision-making is influenced by process, which is deeply intertwined with context and content and the relationship and interaction between influences must be considered

Current adaptation guidance is heavily centred around the process of adaptation decision-making. As a result, academic research studies evaluating the process tend to focus narrowly on the process itself. However, applying the Context, Content and Process (CCP) framework (Pettigrew, 1990) combined with the insight developed through the action based longitudinal case study, this thesis argues that process is heavily influenced and intertwined with the context and content. Failure to acknowledge these two factors when undertaking the adaptation decision-makingdecision-making process is likely to result in significant challenges, delays and poor options appraisal identification, and action.

The context, content and process framework identified several influences challenging adaptation decision-making. The results gathered through action research, demonstrate that organisational adaptation decision-making is strongly related to the internal awareness and buy-in for climate adaptation, enabling policy environment (the context), the data and evidence consulted (the content) and the appraisal steps and mechanisms used to identify and evaluate adaptation options (the process).

Challenges relating to the content used within options evaluations include the lack of locally relevant information, uncertainties present and vagueness of proposed options. Challenges with the actual decision-making process included limited mechanisms to identify options and lack of methods to appraise potential options. These limitations were heightened by lack of awareness, leadership and resource devoted by the organisation and wider environment (the internal and external context).

This research highlights that it is insufficient to study the decision-making process alone, rather it is necessary to understand the wider system structures, goals of action and distribution of power. These findings align with Wise et al. (2014) and Gorddard et al. (2016) who argue that it is not adequate to only examine decision-making processes for risk of obfuscation. Therefore, the broader context in terms of social systems and institutional structures must be studied as it exerts influence on framing and action taking on the problem. The evidence from this study indicates the significance of a multi-factor explanation of change, as advocated for by Pettigrew (1990). Describing and analysing processes of change and how these are enabled and constrained has identified influencing features of context, content, and process. This thesis responds to Biesbroek et al. (2015) call for implementation research to adequately explain barriers and inform processes. Findings show that adapting to climate change is typically not a rational and linear process despite that being explicitly or implicitly assumed by existing academic tools and practitioner guidance (Tangney, 2019).

### 11.2.2 Current adaptation decision-making guidance and research does not sufficiently support the identification and appraisal of adaptation options and leads to hypervigilance

This thesis sought to deepen conceptual and practical knowledge of adaptation decision-making. The majority of current adaptation guidance resources (such as Adaptation Wizard, RESIN, the European Adaptation Support Tool) state the need to identify and appraise adaptation action options, yet they do not provide comprehensive recommendations on how this could be undertaken in practice. In addition, such adaptation resources adopt a cyclical, risk-based, rational approach to decision-making. Findings from this thesis contradict this idealised approach to decision-making, suggesting the adaptation at the city-level, in some cases, is challenged by rational methods. This thesis argues that more structured decision-making processes that adopt participatory processes which incorporate local knowledge are needed to improve climate adaptation in cities.

In observing (and participating in) the adaptation decision-making process, from inception through to options identification and appraisal, the state of hypervigilant decision-making was regularly observed. ‘Hypervigilance’ is a state of decision-making which occurs when a decision maker is stressed due to time and resource constraints and searches frantically for options that address the immediate problem, and all options are not considered using an appropriate decision support method. Hypervigilance is typified by a disorganised and inefficient state (Johnston et al., 1997). This is in opposition to ‘vigilance’ where a decision maker confirms and agrees objectives to be achieved, searches for possible options, collates relevant information, assesses options in an unbiased manner and selects options. The common cause for the state of ‘hypervigilance’ was driven through: (i) the lack of resource; (ii) the short-term political life cycle; (iii) competing priorities; (iv) limited technical skill or training amongst staff; (v) external citizen pressure; and (vi) a decision-making process which does not account for these challenges.

I argue that common interpretations and resources which are meant to assist adaptation practitioners, can actually hinder them by causing hypervigilance. This is because such interpretations make a number of assumptions including access to readily available data, the ability to interpret and use data, sufficient understanding of the problem system, ample time to deliberate and make the decision. Within this study and noted in other published research and interviews with decision makers in the Netherlands and Northern Ireland, the cyclical, smooth and rational approach to adaptation was not found to be the case in practice.

To transition to vigilant decision-making, alternative decision-making methods are required to change the perception of the decision maker and improve understanding of climate adaptation, explore the wide range of potential options, and evaluate their possible consequences and account for CCP influences. In recognition of current guidance insufficiently accounting for the tendency for hypervigilant decision-making, Objective Two of this thesis tested the application of two decision-making tools (BBNs & QPNs) to assess their usefulness in terms of improved options identification and appraisal, a key part in enabling vigilant decision-making.

### 11.2.3 The value of BBN and QPN in aiding city-level adaptation decision-making

This thesis explored the value of two decision-making methods (BBN and QPN). Despite being commonly applied in other decision management fields and their theoretical strengths over other decision-making methods (Section 3.4) their usefulness has not been fully explored in overcoming the challenges specific to city-level adaptation decision-making (identified in Objective One). The methods were found to offer potential to aid adaptation decision-making.

First a BBN exploring resilience to pluvial flooding was developed. In observing stakeholders' interaction with the process, a key finding common to most participants was their discomfort in speaking in the form of probabilities and the difficulties in quantifying aspects of the network which are not able to be seen or studied in practice yet. Despite the limitations of BBN, the process of creating the qualitative structure, including identifying relevant variables and mapping out causal relationship between them, was valued by the decision maker as it aided their understanding of the system and supported consideration of the effects of different adaptation options. The analysis of effectiveness of options and support to perform 'what if' testing to appraise options under different futures was found useful to inform decision-making.

As a result of the learnings from the BBN approach, a QPN was tested in relation to heat resilience. A QPN approach was also observed to bring together diverse knowledge and help identify many potential adaptation options. Due to the nature of QPNs, requiring less elicitation burden and technical skills required, the process was more participatory in nature, with network structure being constructed collectively and group discussions used to identify influence, strength, and synergies within the network to appraise actions.

Overall, the application of BBN and QPN proved valuable in use by decision makers and participating stakeholders. In conducting this study, a clear knowledge gap in the literature emerged in that it is not clearly understood how a decision maker can choose if BBNs or QPNs are appropriate based on their specific context, content and process being used. In recognition of the knowledge gap in the literature (and in public guidance) on how city level adaptation decision makers can choose if BBNs or QPNs are appropriate, a protocol was developed. The protocol supports users to understand if the following options are most suited: (i) BBN; (ii) QPN; (iii) additional capacity building and awareness raising; or (iv) alternative decision support method. The five themes considered in the protocol are: (i) awareness and understanding; (ii) resource, (iii) data availability; (iv) stakeholder participation; and (v) expert elicitation.

Another gap that was identified in the literature and which this research addresses is BBN construction. There is a dearth of contributions on practical techniques for how to construct BBNs with practitioners. There is little mention of how case study circumstances affect the process. This research agrees with Založnik et al. (2021) that further support is needed to inform participatory BBNs and there is merit in pursuing this given the advantages of BBNs as physical and conceptual frameworks for action based research. Similarly, no published studies explore the use of QPNs within climate adaptation. This thesis finds them suitable preliminary tools to aid climate adaptation decision-making at the city-level and advocates for their consideration for use and further research or testing.

## 11.3 Recommendations for future research

Although this thesis was able to shed light on climate adaptation decision-making in practice, it is not without it’s limitations. This section recognises the limitations of this thesis and subsequently recommends opportunities for further research.

- **Further study on traits of hypervigilant decision-making in relation to climate adaptation** – There is scope to refine the CCP framework and explore each influence in more depth and compare across different cities. This detail may help further elucidate how and why hypervigilance occurs. Insight could be gained by using the Melbourne decision-making questionnaire (an instrument for measuring patterns for coping with decisional conflict) (Mann et al., 1997) with adaptation practitioners. In addition, the role of adaptation capabilities or competencies to support vigilance could be explored.

- **Research on additional methods to complement BBNs and QPNs** - Although a preliminary literature review was conducted on a range of different decision-making methods, due to the scope of the research, only two were tested in practice (QPNs and BBNs). As such, application and testing of other decision-making methods to address the challenges identified in Objective One would be valuable. A limitation of this research could be seen as the method choice of using BBNs and QPNs. This is because both methods are acyclic directed graphs which cannot incorporate feedback loops (Catenacci & Giupponi, 2010). Relationships are represented in one-way causal influences, and this may not always be the case in adaptation. Given the benefits of BBNs and QPNs to climate adaptation, identified in this study, there would be merit in exploring which other methods would complement them in practice (potentially as a secondary method). Methods which consider financial implications of the shortlisted adaptation options, would appear to be a natural progression following a BBN or QPN process.

  Another area in which the concept should be broadened is understanding whether the application of the BBN and QPN results in sufficient action and whether such action is effective. This requires a longitudinal post and ex-ante assessment as well as monitoring and evaluation processes in place. Further research on maladaptation, both conceptually and in practice, is also needed (however was outwith the scope of this thesis).

- **Exploration of benefits and trade-offs of enhanced complexity of networks** - The aim of exploring the value of BBN and QPN methods in a real-world setting was not to develop the most perfect networks, rather to use them as vehicles with which to examine the overarching challenges and advantages associated with them in terms of aiding decision-making. The approaches were simplified in some ways in order to aid this objective as well as fit within the time constraint of both this study and the decision-making process unfolding within GCC. As such, there are key weaknesses in the networks, for example, lack of temporality. This could be addressed by instead of using static BBNs (as was done in this thesis) to use dynamic BBNs with multiple timesteps, where temporal dynamics can be studied. Such an approach was not used due to complexity and resource requirements (a dynamic BBN requires more information to quantify time dynamics and uncertainty levels increase, the further into the future the network considers) (Catenacci & Giupponi, 2010). It is also proposed that considering how dynamic BBNs could support adaptation pathway planning approaches may be a fruitful area of research, given the identified advantages in incorporating multiple data sets, supporting ‘what if’ testing and iterative decision-making. Lastly, there is a need to consider how the methods of BBNs and QPNs may support transformational adaptation in particular. Transformational approaches were not studied in this thesis due to their relative absence in the research setting.

- **Additional empirical studies** - Value would be added in comparing and contrasting the challenges associated with city level adaptation decision-making across differing cities to determine generalisable problems faced by decision makers. This study provides a clear and transparent methodology with which to do this. However, as this is an understudied area in the literature, this study focused specifically on one city, largely due to the belief that context in which the decision-making process for each and every city will be unique and so there is greater utility of research in diving deep before looking wide and comparing different cities. Additional insight may also be garnered through comparing decision-making in urban and rural settings. In addition, study on multi-level governance and its impact on decision-making processes would provide useful contributions.

## 11.4 Concluding remarks

Climate change is having widespread consequences across our societies, economies and natural and built environment. Cities are often at the forefront of preparing for and responding to these impacts. With over 70% of the population predicted to be living in cities by 2050, it is critical that city councils overcome challenges to adaptation to make appropriate, well-informed decisions on how to adapt.

Effective adaptation decision-making, whilst critical, is currently limited by an array of challenges or barriers. Overall, this thesis concludes that climate adaptation decision-making is influenced by context, content, and process. For adaptation to be successful, a broader enabling environment is needed. This includes resource and policy to drive adaptation at the local level.

If effective adaptation decision-making is to be achieved, the conceptualisation of adaptation and associated decision-support methods must be redesigned to cope with non-linearity, the pressures driving hypervigilance and the CCP influences identified. Therein lies the contribution of this thesis, which identified factors influencing decision-making in practice, tested new approaches and developed a potential protocol to aid adaptation decision-making. Appropriate decision support also helps ensure effective adaptation choices are being made. BBNs and QPNs are potential methods to help decision makers identify and appraise which options are suitable to achieve their objectives given their local context.

This thesis is a call to action. If society is to adapt to climate change, we must make decisions about the future today. By developing and applying tools which aid vigilant decision-making in a non-linear context, city councils can begin to make effective climate adaptation decisions, enabling businesses, communities, and individuals all to be more resilient in the face of our changing climate.

## References


Action on Climate Today. (2016). *Prioritising climate change adaptation actions: the need for prioritisation* (Vol. 8).

Action research for climate change adaptation : Developing and applying knowledge for governance. (2015). In A. van Buuren, J. Eshuis, & M. van Vliet (Eds.), *Action Research for Climate Change Adaptation*. Routledge.

Adaptation Scotland. (2013). *Five steps to managing your climate risks: A Guide for Public Bodies in Scotland*.

Adaptation Scotland. (2021). *Climate Projections for Scotland*. Retrieved from https://www.adaptationscotland.org.uk/application/files/5816/1797/9967/LOW_RES_4656_Climate_Projections_report_FINAL.pdf

Adedeji, T. , Proverbs, D. G., Xiao, H., & Oladokun, V. O. (2018). Towards a conceptual framework for property level flood resilience. *International Journal of Safety and Security Engineering*, *8*(4), 493–504. https://doi.org/10.2495/SAFE-V8-N4-493-504

Adger, W. N. (2003). Social Capital, Collective Action, and Adaptation to Climate Change. *Economic Geography*, *79*(4), 387–404. https://doi.org/10.1111/j.1944-8287.2003.tb00220.x

Adger,N.(2006). Vulnerability. *Global Environmental Change*, *16*(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Adger, N., & Barnett, J. (2009). Four Reasons for Concern about Adaptation to Climate Change. *Environment and Planning A: Economy and Space*, *41*(12), 2800–2805. https://doi.org/10.1068/a42244

Adger, N. , Arnell, N. W., & Tompkins, E. L. (2005). Successful adaptation to climate change across scales. *Global Environmental Change*, *15*(2), 77–86. https://doi.org/10.1016/j.gloenvcha.2004.12.005

Adler, C., Cheong, S., Conde, C., Constable, A., Coughlan de Perez, E., Lammel, A., … Solecki, W. (n.d.). Chapter 17: Decision-making Options for Managing Risk. In *IPCC WGII Sixth Assessment Report* (Vol. 3, pp. 1–236). (Forthcoming).

Agee, J. (2009). Developing qualitative research questions: A reflective process. *International Journal of Qualitative Studies in Education*, *22*(4), 431–447. https://doi.org/10.1080/09518390902736512

Agrawal, A. (2008). The Role of Local Institutions in Adaptation to Climate Change. In

*The Role of Local Institutions in Adaptation to Climate Change*. https://doi.org/10.1596/28274

Aguilera, P. A., Fernández, A., Fernández, R., Rumí, R., & Salmerón, A. (2011). Bayesian networks in environmental modelling. *Environmental Modelling & Software*, *26*(12), 1376–1388. https://doi.org/10.1016/j.envsoft.2011.06.004

Aksu, G., Güzeller, C. O., & Eser, M. T. (2019). The Effect of the Normalization Method Used in Different Sample Sizes on the Success of Artificial Neural Network Model. *International Journal of Assessment Tools in Education*, *6*(2), 170–192. https://doi.org/10.21449/ijate.479404Almansa, Carmen, and José M. Martínez-Paz. 2011. “What Weight Should Be Assigned to Future Environmental Impacts? A Probabilistic Cost Benefit Analysis Using Recent Advances on Discounting.” *Science of the Total Environment* 409(7): 1305–14. http://dx.doi.org/10.1016/j.scitotenv.2010.12.004.

Allen, M.R., O.P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu, and K. Z. (2018). Framing and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the. In and T. W. (eds Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].Masson- (Ed.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways*. https://doi.org/10.1017/CBO9781107415324.004

Amundsen, H., Berglund, F., & Westskog, H. (2010). Overcoming Barriers to Climate Change Adaptation—A Question of Multilevel Governance? *Environment and Planning C: Government and Policy*, *28*(2), 276–289. https://doi.org/10.1068/c0941

Andersson-Sköld, Y., Thorsson, S., Rayner, D., Lindberg, F., Janhäll, S., Jonsson, A., … Granberg, M. (2015). An integrated method for assessing climate-related risks and adaptation alternatives in urban areas. *Climate Risk Management*, *7*, 31–50.

https://doi.org/10.1016/j.crm.2015.01.003

Arnell, N. W. (2010). Adapting to climate change: an evolving research programme. *Climatic Change*, *100*(1), 107–111. https://doi.org/10.1007/s10584-010-9839-0

Baer, P., & Spash, C. L. (2008). *Cost-Benefit Analysis of Climate Change: Stern Revisited*.

Baines, P., & Lynch, R. (2005). The Context, Content and Process of Political Marketing Strategy. *Journal of Political Marketing*, *4*(2–3), 1–18. https://doi.org/10.1300/J199v04n02_01

Baker, I., Peterson, A., Brown, G., & McAlpine, C. (2012). Local government response to the impacts of climate change: An evaluation of local climate adaptation plans. *Landscape and Urban Planning*, *107*(2), 127–136. https://doi.org/10.1016/j.landurbplan.2012.05.009

Baker, Z., Ekstrom, J., & Bedsworth, L. (2018). Climate information? Embedding climate futures within temporalities of California water management. *Environmental Sociology*, *4*(4), 419–433. https://doi.org/10.1080/23251042.2018.1455123

Balamuralidhar, P. (2013). An approach using Qualitative Probabilistic Networks for knowledge modeling in Cognitive Wireless Networks. *Wireless VITAE 2013*, 1–5. https://doi.org/10.1109/VITAE.2013.6617055

Balbi, S., Villa, F., Mojtahed, V., Hegetschweiler, K. T., & Giupponi, C. (2015). A spatial Bayesian network model to assess the benefits of early warning for urban flood risk to people. *Natural Hazards and Earth System Sciences Discussions*, *3*(10), 6615–6649. https://doi.org/doi:10.5194/nhessd-3-6615-2015

Ballard, D., Bond, C., Pyatt, N., Lonsdale, K., Whitham, D., Dessai, S., … Tweed, J. (2013). *PREPARE - Barriers and enablers to organisational and sectoral adaptive capacity – qualitative study*.

Bardwell, Lisa V. 1991. “Problem-Framing: A Perspective on Environmental Problem-Solving.” *Environmental Management* 15(5): 603–12.

Barnett, J., Evans, L. S., Gross, C., Kiem, A. S., Kingsford, R. T., Palutikof, J. P., … Smithers, S. G. (2015a). From barriers to limits to climate change adaptation: path dependency and the speed of change. *Ecology and Society*, *20*(3), art5. https://doi.org/10.5751/ES-07698-200305

Barnett, J., Evans, L. S., Gross, C., Kiem, A. S., Kingsford, R. T., Palutikof, J. P., … Smithers, S. G. (2015b). From barriers to limits to climate change adaptation: Path dependency and the speed of change. *Ecology and Society*, *20*(3). https://doi.org/10.5751/ES-07698-200305

Barnett, J., & O'Neill, S. (2010). Maladaptation. *Global Environmental Change*, *20*(2), 211–213. https://doi.org/10.1016/j.gloenvcha.2009.11.004

Baskerville, R., & Wood-Harper, A. T. (1998). Diversity in information systems action research methods. *European Journal of Information Systems*, *7*(2), 90–107. https://doi.org/10.1057/palgrave.ejis.3000298

Bayes Fusion LLC. (2020a). *GeNIe Modeler: Complete Modeling Freedom*. Retrieved from https://www.bayesfusion.com/genie/

Bayes Fusion LLC. (2020b). *QGeNIe Modeler User Manual*. Retrieved from Version 3.0 R2 website: https://support.bayesfusion.com/docs/QGeNIe.pdf

Bedford, T., & Cooke, R. (2001). *Probabilistic Risk Analysis*. https://doi.org/10.1017/CBO9780511813597

Bell, G. G., Bromiley, P., & Bryson, J. (1997). Spinning a Complex Web: Links between Strategic Decision-making Context, Content, Process, and Outcome. In V. Papadakis & P. Barwise (Eds.), *Strategic Decisions* (pp. 163–178). https://doi.org/10.1007/978-1-4615-6195-8_11

Bellingham, R. (2010). *Sustainable Glasgow*. Retrieved from https://pureportal.strath.ac.uk/files-asset/30698715/FEC_33_3_2010_BellinghamR.pdf

Berkhout, F. (2012). Adaptation to climate change by organizations. *WIREs Clim Change*, *3*(1), 91–106. https://doi.org/10.1002/wcc.154

Berkhout, F., Hertin, J., & Gann, D. M. (2006). Learning to Adapt: Organisational Adaptation to Climate Change Impacts. *Climatic Change*, *78*(1), 135–156. https://doi.org/10.1007/s10584-006-9089-3

Berrang-Ford, L., Ford, J. D., & Paterson, J. (2011). Are we adapting to climate change? *Global Environmental Change*, *21*(1), 25–33. https://doi.org/10.1016/j.gloenvcha.2010.09.012

Berrang-Ford, L., Pearce, T., & Ford, J. D. (2015). Systematic review approaches for climate change adaptation research. *Regional Environmental Change*, *15*(5), 755–769. https://doi.org/10.1007/s10113-014-0708-7

Beumer, M. (2006). *Qualitative Probabilistic Networks in Medical Diagnosis*. University of Amsterdam.

Biagini, B., Bierbaum, R., Stults, M., Dobardzic, S., & McNeeley, S. M. (2014). A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. *Global Environmental Change*, *25*(1), 97–108. https://doi.org/10.1016/j.gloenvcha.2014.01.003

Biedermann, A., & Taroni, F. (2006). Bayesian networks and probabilistic reasoning about scientific evidence when there is a lack of data. *Forensic Science International*, *157*(2–3), 163–167. https://doi.org/10.1016/j.forsciint.2005.09.008

Bierbaum, R., Smith, J. B., Lee, A., Blair, M., Carter, L., Chapin, F. S., … Verduzco, L. (2013). A comprehensive review of climate adaptation in the United States: more than before, but less than needed. *Mitigation and Adaptation Strategies for Global Change*, *18*(3), 361–406. https://doi.org/10.1007/s11027-012-9423-1

Biesbroek, G. G. R., Termeer, C. J. A. M., Kabat, P., & Klostermann, J. E. M. (2009). Institutional governance barriers for the development and implementation of climate adaptation strategies. In *Working paper for the International Human Dimensions Programme (IHDP) conference "Earth System Governance: People, Places, and the Planet", December 2-4, Amsterdam, the Netherlands*.

Biesbroek, G. R., Klostermann, J. E. M., Termeer, C. J. A. M., & Kabat, P. (2013). On the nature of barriers to climate change adaptation. *Regional Environmental Change*, *13*(5), 1119–1129. https://doi.org/10.1007/s10113-013-0421-y

Biesbroek, G. R., Swart, R. J., & van der Knaap, W. G. M. (2009). The mitigation–adaptation dichotomy and the role of spatial planning. *Habitat International*, *33*(3), 230–237. https://doi.org/10.1016/j.habitatint.2008.10.001

Biesbroek, R., Dupuis, J., Jordan, A., Wellstead, A., Howlett, M., Cairney, P., … Davidson, D. (2015). Opening up the black box of adaptation decision-making. *Nature Climate Change*, *5*(6), 493–494. https://doi.org/10.1038/nclimate2615

Biesbroek, R., Klostermann, J., Termeer, C., & Kabat, P. (2011). Barriers to climate change adaptation in the Netherlands. *Climate Law*, *2*(2), 181–199. https://doi.org/10.3233/CL-2011-033

Bisaro, A., Roggero, M., & Villamayor-Tomas, S. (2018). Institutional Analysis in Climate Change Adaptation Research: A Systematic Literature Review. *Ecological Economics*, Vol. 151, pp. 34–43.

https://doi.org/10.1016/j.ecolecon.2018.04.016

Blanco G., R. Gerlagh, S. Suh, J. Barrett, H. C. de Coninck, C. F. Diaz Morejon, R. Mathur, N. Nakicenovic, A. Ofosu Ahenkora, J. Pan, H. Pathak, J. Rice, R. Richels, S. J. Smith, D. I. Stern, F. L. Toth, and P. Z. (2014). Drivers, Trends and Mitigation. In T. Z. and J. C. M. (eds. )]. Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow (Ed.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 351–412). Cambridge, United Kingdom and New York, NY, USA.

Blum, F. (1955). Action Research - A Scientific Approach? *Philosphy of Science*, *22*(1), 1–7.

Bolt, J. H., Van Der Gaag, L. C., & Renooij, S. (2005). Introducing situational signs in qualitative probabilistic networks. In *technical report UU-CS-2004-006* (Vol. 38). https://doi.org/10.1016/j.ijar.2004.05.009

Bosello, F., Carraro, C., & De Cian, E. (2009). An Analysis of Adaptation as a Response to Climate Change. In *Working Papers Department of Economics Ca' Foscari University of Venice*. https://doi.org/10.2139/ssrn.1513286

Bowyer, P., Bender, S., Rechid, D., & Schaller, M. (2014). Handbook of Climate Change Adaptation. In W. Leal Filho (Ed.), *Climate Service Center*. https://doi.org/10.1007/978-3-642-38670-1

Brace, C., & Geoghegan, H. (2011). Human geographies of climate change: Landscape, temporality, and lay knowledges. *Progress in Human Geography*, *35*(3), 284–302. https://doi.org/10.1177/0309132510376259

Bradford, R. A., O'Sullivan, J. J., van der Craats, I. M., Krywkow, J., Rotko, P., Aaltonen, J., … Schelfaut, K. (2012). Risk perception – issues for flood management in Europe. *Natural Hazards and Earth System Sciences*, *12*(7), 2299–2309. https://doi.org/10.5194/nhess-12-2299-2012

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bree, L. Van, & Sluijs, J. Van Der. (2014). Background on Uncertainty Assessment

Supporting Climate Adaptation. In *Adapting to an Uncertain Climate Lessons from Practice* (pp. 17–40). https://doi.org/10.1007/978-3-319-04876-5

Breierova, L., & Choudhari, M. (1996). An Introduction to Sensitivity Analysis. In *Prepared for the MIT System Dynamics in Education Project*. https://doi.org/10.1016/j.epsr.2009.03.004

Bremner, A., & Park, K. (2007). Public attitudes to the management of invasive non-native species in Scotland. *Biological Conservation*, *139*(3–4), 306–314. https://doi.org/10.1016/j.biocon.2007.07.005

Brooks, N. (2003). Vulnerability, risk and adaptation: A conceptual framework. Tyndall Centre for Climate Change Research. *Tyndall Centre for Climate Change Research*, (February), 1–20.

Brooks, N., Neil Adger, W., & Mick Kelly, P. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*, *15*(2), 151–163. https://doi.org/10.1016/j.gloenvcha.2004.12.006

Brown, A., Gawith, M., Lonsdale, K., & Pringle, P. (2011). *Managing adaptation: linking theory and practice*. Retrieved from www.ukcip.org.uk

Brownlee, M. T. J., Hallo, J. C., & Krohn, B. D. (2013). Botanical garden visitors' perceptions of local climate impacts: awareness, concern, and behavioral responses. *Managing Leisure*, *18*(2), 97–117. https://doi.org/10.1080/13606719.2013.752209

Buchannan, L. ;, & O'Connell, A. (2006). A Brief History of Decision-making. *Harvard Business Review*. Retrieved from https://hbr.org/2006/01/a-brief-history-of-decision-making

Buchner, B., Clark, A., Falconer, A., Macquarie, C., Tolentino, R., & Watherbee, C. (2019). Global Landscape of Climate Finance 2019. In *Climate Policy Initiative*. Retrieved from https://www.climatepolicyinitiative.org/wp-content/uploads/2019/11/2019-Global-Landscape-of-Climate-Finance.pdf

Bulkeley, H. (2010). Cities and the Governing of Climate Change. *Annual Review of Environment and Resources*, *35*(1), 229–253. https://doi.org/10.1146/annurev-environ-072809-101747

Bulkeley, H. (2013). Cities and Climate Change. In *Cities and Climate Change*. https://doi.org/10.4324/9780203077207

Bulkeley, H., Schroeder, H., Janda, K., Zhao, J., Armstrong, A., Chu, S. Y., & Ghosh, S. (2011). The Role of Institutions, Governance, and Urban Planning for Mitigation and Adaptation. In *Cities and Climate Change* (pp. 125–159). https://doi.org/10.1596/9780821384930_CH05

Burt, G., & van der Heijden, K. (2003). First steps: towards purposeful activities in scenario thinking and future studies. *Futures*, *35*(10), 1011–1026. https://doi.org/10.1016/S0016-3287(03)00065-X

Burton, I., Kates, R. W., & White, G. F. (1993). *The Environment as Hazard*. Guilford Press.

Buurman, J., & Babovic, V. (2016). Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society*, *35*(2), 137–150. https://doi.org/10.1016/j.polsoc.2016.05.002

C40 Cities. (2021). C40 Cities - What We Do. Retrieved March 1, 2021, from https://www.c40.org/

C40 Cities, & UCCRN. (2018). *The future we don't want: how climate change could impact the World's Greatest Cities*. Retrieved from https://c40-production-images.s3.amazonaws.com/other_uploads/images/1789_Future_We_Don't_Want_Report_1.4_hi-res_120618.original.pdf

Cain, J. (2001). *Planning improvements in natural resources management: Guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond*.

Cairney, P., & Jones, M. D. (2016). Kingdon's Multiple Streams Approach: What Is the Empirical Impact of this Universal Theory? *Policy Studies Journal*, *44*(1), 37–58. https://doi.org/10.1111/psj.12111

Capela Lourenço, T., Cruz, M. J., Carlsen, H., Dzebo, A., Tàbara, J. D., Cots, F., … Harrison, P. (2015). *Common Frame of Reference to support the understanding of adaptation decision-making under high-end scenarios - Deliverable 1.1*.

Capela Lourenço, T., Rovisco, A., Groot, A., Nilsson, C., Füssel, H. M., Van Bree, L., & Street, R. B. (2014). Adapting to an Uncertain Climate. In T. Capela Lourenço, A. Rovisco, A. Groot, C. Nilsson, H.-M. Füssel, L. Van Bree, & R. B. Street (Eds.), *Adapting to an Uncertain Climate: Lessons from Practice*. https://doi.org/10.1007/978-3-319-04876-5

Cardona, O.-D., van Aalst, M. K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., … Thomalla, F. (2012). Determinants of Risk: Exposure and Vulnerability. In Christopher B. Field, V. Barros, T. F. Stocker, & Q. Dahe (Eds.), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (pp. 65–108). https://doi.org/10.1017/CBO9781139177245.005

Carter, D. K. (2016). *Remaking Post-Industrial Cities, Lessons from north America and Europe*.

Carter, J. G., Cavan, G., Connelly, A., Guy, S., Handley, J., & Kazmierczak, A. (2015a). Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, *95*, 1–66. https://doi.org/10.1016/j.progress.2013.08.001

Carter, J. G., Cavan, G., Connelly, A., Guy, S., Handley, J., & Kazmierczak, A. (2015b). Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, *95*, 1–66. https://doi.org/10.1016/j.progress.2013.08.001

Castán Broto, V., & Bulkeley, H. (2013). A survey of urban climate change experiments in 100 cities. *Global Environmental Change*, *23*(1), 92–102. https://doi.org/10.1016/j.gloenvcha.2012.07.005

Castelletti, A., & Soncini-Sessa, R. (2006). A procedural approach to strengthening integration and participation in water resource planning. *Environmental Modelling & Software*, *21*(10), 1455–1470. https://doi.org/10.1016/j.envsoft.2005.07.013

Castillo, E., Gutierrez, J. M., & Hadi, A. S. (1997). Sensitivity analysis in discrete Bayesian networks. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, *27*(4), 412–423. https://doi.org/10.1109/3468.594909

Castillo, E., Gutierrez, J. M., & Hadi, A. S. (1997). Sensitivity analysis in discrete Bayesian networks. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, *27*(4), 412–423. https://doi.org/10.1109/3468.594909

Catenacci, M.; Giuponni, C. (2008). Integrated methodology for the management of uncertainty and complexity in climate change adaptation policies : a Bayesian Decision Network approach. *International Congress on Environmental Modelling and Software*.

Catenacci, M, & Giupponi, C. (2009). Potentials of Bayesian networks to deal with uncertainty in climate change adaptation policies. *Catenacci, Michela Giupponi, Carlo*, (October), 1–30. https://doi.org/10.2139/ssrn.1526605

Catenacci, M. & Giupponi, C. (2009). Potentials of Bayesian Networks to Deal with Uncertainty in Climate Change Adaptation Policies. In *Centro Euro-Mediterraneo* *per i Cambiamenti Climatici*. https://doi.org/10.2139/ssrn.1526605

Catenacci, Michela, & Giupponi, C. (2010). Potentials and limits of bayesian networks to deal with uncertainty in the assessment of climate change adaptation policies. In *Sustainable Development series*.

Cavana, R., & Maani, K. (2000). A Methodological Framework for Integrating Systems Thinking and System Dynamics. *Technology*, 49–50. Retrieved from http://www.systemdynamics.org/conferences/2000/PDFs/cavana41.pdf

Chapman, E. (2018). *User Guide : the Resin Decision Support Tools for Climate*. Freiburg.

Chen, C., Doherty, M., Coffee, J., Wong, T., & Hellmann, J. (2016). Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas. *Environmental Science and Policy*, *66*, 403–419. https://doi.org/10.1016/j.envsci.2016.05.007

Chen, S. H., & Pollino, C. A. (2012). Good practice in Bayesian network modelling. *Environmental Modelling & Software*, *37*, 134–145. https://doi.org/10.1016/j.envsoft.2012.03.012

Cimato, F., & Mullan, M. (2010). Adapting to Climate Change: Analysing the Role of Government. In *Defra Evidence and Analysis Series*.

Clar, C., & Steurer, R. (2018). Why popular support tools on climate change adaptation have difficulties in reaching local policy-makers: Qualitative insights from the UK and Germany. *Environmental Policy and Governance*, *28*(3), 172–182. https://doi.org/10.1002/eet.1802

Clare, A., Graber, R., Jones, L., & Conway, D. (2017). Subjective measures of climate resilience: What is the added value for policy and programming? *Global Environmental Change*, *46*(October 2016), 17–22. https://doi.org/10.1016/j.gloenvcha.2017.07.001

Climate Action Tracker. (2020). Evaluating progress towards the Paris Agreement. Retrieved November 1, 2021, from https://climateactiontracker.org/global/temperatures/

Climate Analytics, & NewClimate. (2021). *Warming Projections Global Update*. Retrieved from https://climateactiontracker.org/publications/glasgows-2030-credibility-gap-net-zeros-lip-service-to-climate-action/

Climate Ready Clyde. (2020). Climate Ready Clyde: Building a more resilient, prosperous and fairer Glasgow City Region. Retrieved November 1, 2021, from http://climatereadyclyde.org.uk/

ClimateXChange. (2016a). BB13 Proportion of local authority areas under impermeable surfaces; Change in impermeable surfacing in built-up areas. In *Indicators and Trends*. Retrieved from https://academic.oup.com/jnci/article/30/4/845/868142/Indicators-and-Trends

ClimateXChange. (2016b). *Indicators and trends: monitoring climate change adaptation. BE5 Electricity substations located in areas at flood risk*.

ClimateXChange. (2016c). *Indicators and trends: Monitoring climate change adaptation. BT2 Road network at risk of flooding*.

CoastAdapt. (2017). The adaptation process Coastal Climate Adaptation Decision Support (C-CADS). Retrieved October 17, 2019, from https://coastadapt.com.au/coastal-climate-adaptation-decision-support-c-cads

Coghlan, David; Brannick, T. (2005). *Doing Action in Your Own*. London: SAGE Publications Ltd.

Coleman, J. (1988). Social Capital in the Creation of Human Capital Author. *The American Journal of Sociology*, *94*(Supplement: Organizations and Institutions: Sociological and Economic Approaches to the Analysis of Social Structure), S95–S120.

Collier, Z. A., Linkov, I., & Lambert, J. H. (2014). Tools and strategies for climate change decision-making. *Environment Systems and Decisions*, *34*(4), 471–472. https://doi.org/10.1007/s10669-014-9527-0

Colson, A. R., & Cooke, R. M. (2018). Expert Elicitation: Using the Classical Model to Validate Experts' Judgments. *Review of Environmental Economics and Policy*, *12*(1), 113–132. https://doi.org/10.1093/reep/rex022

Constantinou, A. C., & Fenton, N. (2018). Things to know about Bayesian networks: Decisions under uncertainty, part 2. *Significance Magazine*, *15*(2), 19–23. https://doi.org/10.1111/j.1740-9713.2018.01126.x

Cooke, R. (1991). *Experts in Uncertainty: Opinion and Subjective Probability in Science.* New York, NY: Oxford University Press.

Cooke, R. M., & Goossens, L. L. H. J. (2008). TU Delft expert judgment data base. *Reliability Engineering and System Safety*, *93*(5), 657–674. https://doi.org/10.1016/j.ress.2007.03.005

Coupé, V. M. H., Peek, N., Ottenkamp, J., & Habbema, J. D. F. (1999). Using sensitivity analysis for efficient quantification of a belief network. *Artificial Intelligence in Medicine*, *17*(3), 223–247. https://doi.org/10.1016/S0933-3657(99)00024-X

Coupe, V. M. H., & Van der Gaag, L. (1998). *Practicable Sensitivity Analysis of Bayesian Belief Networks*.

Crabbé, P., & Robin, M. (2006). Institutional Adaptation of Water Resource Infrastructures to Climate Change in Eastern Ontario. *Climatic Change*, *78*(1), 103–133. https://doi.org/10.1007/s10584-006-9087-5

Craig, R. K. (2010). "Stationary is dead" - long live transformation: Five principles for climate change adaptation law. *Harvard Environmental Law Review*, *34*.

Crowley, K., & Head, B. W. (2017). The enduring challenge of 'wicked problems': revisiting Rittel and Webber. *Policy Sciences*, *50*(4), 539–547. https://doi.org/10.1007/s11077-017-9302-4

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). A place-based model for understanding community resilience to natural disasters. *Global Environmental Change*, *18*(4), 598–606. https://doi.org/10.1016/j.gloenvcha.2008.07.013

da Silva, J., Kernaghan, S., & Luque, A. (2012). A systems approach to meeting the challenges of urban climate change. *International Journal of Urban Sustainable Development*, *4*(2), 125–145. https://doi.org/10.1080/19463138.2012.718279

Daddi, T., Todaro, N. M., De Giacomo, M. R., & Frey, M. (2018). A Systematic Review of the Use of Organization and Management Theories in Climate Change Studies. *Business Strategy and the Environment*, *27*(4), 456–474. https://doi.org/10.1002/bse.2015

Dambacher, J. M., Shenton, W., & Hayes, K. R. (2007). Qualitative modelling and Bayesian network analysis for risk-based biosecurity decision-making in complex systems ACERA project. In *CSIRO*.

David, P. A. (2007). Path dependence: a foundational concept for historical social science. *Cliometrica*, *1*(2), 91–114. https://doi.org/10.1007/s11698-006-0005-x

Davison, R. M., & Martinsons, M. G. (2007). Chapter 16 Action Research and Consulting : Hellish Partnership or Heavenly Marriage ? In N. Kock (Ed.), *Information Systems Action Research -An Applied View of Emerging Concepts* *and Methods* (p. 439). Laredo, Texas: Springer.

De Campos, C. P., & Ji, Q. (2011). Efficient structure learning of Bayesian networks using constraints. *Journal of Machine Learning Research*, *12*, 663–689.

de Campos, C. P., Zhang, L., Tong, Y., & Ji, Q. (2009). Semi-Qualitative Probabilistic Networks in Computer Vision Problems. *Journal of Statistical Theory and Practice*, *3*(1), 197–210. https://doi.org/10.1080/15598608.2009.10411920

de Nijs, P. J., Berry, N. J., Wells, G. J., & Reay, D. S. (2015). Quantification of biophysical adaptation benefits from Climate-Smart Agriculture using a Bayesian Belief Network. *Scientific Reports*, *4*(1), 6682. https://doi.org/10.1038/srep06682

Defra. (2020). *Accounting for the effects of climate change - Supplementary Green Book Guidance*.

del Campo, C., Pauser, S., Steiner, E., & Vetschera, R. (2016). Decision-making styles and the use of heuristics in decision-making. *Journal of Business Economics*, *86*(4), 389–412. https://doi.org/10.1007/s11573-016-0811-y

Dessai, S. & van der Sluijs, J. (2007). Uncertainty and climate change adaptation -a ScopingStudy. In *Copernicus Insititute Research Institute for Sustainable Development and Innovation*. Retrieved from papers://ef64220a-a077-48ec-ae81-be13b32d2073/Paper/p27

Dessai, S. & Hulme, M. (2004). Does climate adaptation policy need probabilities? *Climate Policy*, *4*(2), 107–128. https://doi.org/10.1080/14693062.2004.9685515

Dessai, S. Lu, X., & Risbey, J. S. (2005). On the role of climate scenarios for adaptation planning. *Global Environmental Change*, *15*(2), 87–97. https://doi.org/10.1016/j.gloenvcha.2004.12.004

Devilee, J., & Knol, A. (2011). *Software to support expert elicitation An exploratory study of existing software Software to support expert elicitation*.

Devos, G., Buelens, M., & Bouckenooghe, D. (2007). Contribution of Content, Context, and Process to Understanding Openness to Organizational Change: Two Experimental Simulation Studies. *The Journal of Social Psychology*, *147*(6), 607–630. https://doi.org/10.3200/SOCP.147.6.607-630

Dhami, S., Al-Nowaihi, A., & Sunstein, C. R. (2019). Heuristics and Public Policy: Decision-making Under Bounded Rationality. *Studies in Microeconomics*, *7*(1), 7–58. https://doi.org/10.1177/2321022219832148

Dittrich, R., Wreford, A., & Moran, D. (2016). A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics*, *122*, 79–89. https://doi.org/10.1016/j.ecolecon.2015.12.006

Doberstein, B., Fitzgibbons, J., & Mitchell, C. (2019). Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience. *Natural Hazards*, *98*(1), 31–50. https://doi.org/10.1007/s11069-018-3529-z

Dodman, D., & Carmin, J. (2011). Urban adaptation planning: the use and limits of climate science. In *IIED Briefing: Lessons from adaptation in practice*. Retrieved from http://pubs.iied.org/17108IIED.html

Doria, M. de F., Boyd, E., Tompkins, E. L., & Adger, W. N. (2009). Using expert elicitation to define successful adaptation to climate change. *Environmental Science & Policy*, *12*(7), 810–819. https://doi.org/10.1016/j.envsci.2009.04.001

Dragicevic, S., Celar, S., & Turic, M. (2017). Bayesian network model for task effort estimation in agile software development. *Journal of Systems and Software*, *127*, 109–119. https://doi.org/10.1016/j.jss.2017.01.027

Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., … Swingedouw, D. (2015). Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models. *Proceedings of the National Academy of Sciences*, *112*(43), E5777–E5786. https://doi.org/10.1073/pnas.1511451112

Druzdel, M. (1996). Rapid Modeling and Analysis with QG E NI E. *Proceedings of the International Multiconference on Computer Science and Information Technology*, 101–108.

Druzdzel, M. J. (1996). Qualitiative verbal explanations in Bayesian belief networks. *Artificial Intelligence and Simulation of Behaviour Quarterly*, *94*, 43–54.

Dunford, R., Harrison, P. A., & Rounsevell, M. D. A. (2014). Exploring scenario and model uncertainty in cross-sectoral integrated assessment approaches to climate change impacts. *Climatic Change*, *132*(3), 417–432. https://doi.org/10.1007/s10584-014-1211-3

Dupuis, J., & Biesbroek, R. (2013). Comparing apples and oranges: The dependent variable problem in comparing and evaluating climate change adaptation policies. *Global Environmental Change*, *23*(6), 1476–1487. https://doi.org/10.1016/j.gloenvcha.2013.07.022

Dyer, J. S. (2005). Chapter 7 MAUT- Multiattribute Utility Theory. In J. Figueira, S.

Greco, & M. Ehgrott (Eds.), *Multiple Criteria Decision Analysis: State of the Art Surveys* (pp. 265–295). Springer.

Edelenbos, J., & Klijn, E.-H. (2006). Managing Stakeholder Involvement in Decision-making: A Comparative Analysis of Six Interactive Processes in the Netherlands. *Journal of Public Administration Research and Theory*, *16*(3), 417–446. https://doi.org/10.1093/jopart/mui049

Edwards, W. (1954). The theory of decision-making. *Psychological Bulletin*, *51*(4), 380–417. https://doi.org/10.1037/h0053870

Einecker, R., & Kirby, A. (2020). Climate Change: A Bibliometric Study of Adaptation, Mitigation and Resilience. *Sustainability*, *12*(17), 6935. https://doi.org/10.3390/su12176935

Eisenack, K., Moser, S. C., Hoffmann, E., Klein, R. J. T., Oberlack, C., Pechan, A., … Termeer, C. J. A. M. (2014). Explaining and overcoming barriers to climate change adaptation. *Nature Climate Change*, *4*(10), 867–872. https://doi.org/10.1038/nclimate2350

Eiser, J. R., Bostrom, A., Burton, I., Johnston, D. M., McClure, J., Paton, D., … White, M. P. (2012). Risk interpretation and action: A conceptual framework for responses to natural hazards. *International Journal of Disaster Risk Reduction*, *1*, 5–16. https://doi.org/10.1016/j.ijdrr.2012.05.002

Ekstrom, J. A., & Moser, S. C. (2014). Identifying and overcoming barriers in urban climate adaptation: Case study findings from the San Francisco Bay Area, California, USA. *Urban Climate*, *9*, 54–74. https://doi.org/10.1016/j.uclim.2014.06.002

Emmanuel, R., & Krüger, E. (2012). Urban heat island and its impact on climate change resilience in a shrinking city: The case of Glasgow, UK. *Building and Environment*, *53*, 137–149. https://doi.org/10.1016/j.buildenv.2012.01.020

Engle, N. L. (2011). Adaptive capacity and its assessment. *Global Environmental Change*, *21*(2), 647–656. https://doi.org/10.1016/j.gloenvcha.2011.01.019

Engle, N. L., de Bremond, A., Malone, E. L., & Moss, R. H. (2014). Towards a resilience indicator framework for making climate-change adaptation decisions. *Mitigation and Adaptation Strategies for Global Change*, *19*(8), 1295–1312. https://doi.org/10.1007/s11027-013-9475-x

EPA. (2021). Climate Change Indicators: Greenhouse Gases. Retrieved October 13, 2021, from https://www.epa.gov/climate-indicators/greenhouse-gases

ERDF. (2021). URBACT. Retrieved December 27, 2021, from https://urbact.eu/

Eriksen, S. H., Nightingale, A. J., & Eakin, H. (2015). Reframing adaptation: The political nature of climate change adaptation. *Global Environmental Change*, *35*, 523–533. https://doi.org/10.1016/j.gloenvcha.2015.09.014

Etzioni. (1992). Decision-making. In *Rational Decision-making*.

Falloon, P., Challinor, A., Dessai, S., Hoang, L., Johnson, J., & Koehler, A.-K. (2014). Ensembles and uncertainty in climate change impacts. *Frontiers in Environmental Science*, *2*(July), 1–7. https://doi.org/10.3389/fenvs.2014.00033

Fankhauser, S., Smith, J. B., & Tol, R. S. J. (1999). *Weathering climate change : some simple rules to guide adaptation decisions*. *30*, 67–78.

Feenstra, J. F., Burton, I., Smith, J. B., & Tol, R. S. J. (1998). Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies. In *Institute for Environmental Studies IVM Vrije Universiteit Amsterdam*. https://doi.org/10.1111/gcb.12365

Fenton, N.; Neil, M. (2019). *Risk Assessment and Decision Analysis with Bayesian Networks* (Second Edi). CRC Press.

Fenton, N. E., Neil, M., & Caballero, J. G. (2007). Using Ranked Nodes to Model Qualitative Judgments in Bayesian Networks. *IEEE Transactions on Knowledge and Data Engineering*, *19*(10), 1420–1432. https://doi.org/10.1109/TKDE.2007.1073

Fenton, N., & Neil, M. (2001). *Making Decisions: Using Bayesian Nets and MCDA’*. Retrieved from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.65.3992&rep=rep1&type=pdf

Fenton, N., & Neil, M. (2018). *Risk Assessment and Decision Analysis with Bayesian Networks* (2nd Editio; Chapman and Hall / CRC, Ed.). https://doi.org/10.1201/b21982

Ferretto, A., Brooker, R., Aitkenhead, M., Matthews, R., & Smith, P. (2019). Potential carbon loss from Scottish peatlands under climate change. *Regional Environmental Change*, *19*(7), 2101–2111. https://doi.org/10.1007/s10113-019-01550-3

Field, C.B., Barros, V. R., Mach, K. ., Mastrandrea, M. D., Aalst, M. van, Adger, W. N., … Yohe, G. W. (2014). IPCC 2014 Impacts - Technical Summary. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York, NY.

Fincher, R., Barnett, J., & Graham, S. (2015). Temporalities in Adaptation to Sea-Level Rise. *Annals of the Association of American Geographers*, *105*(2), 263–273. https://doi.org/10.1080/00045608.2014.988101

Ford, J. D., Berrang-Ford, L., & Paterson, J. (2011). A systematic review of observed climate change adaptation in developed nations. *Climatic Change*, *106*(2), 327–336. https://doi.org/10.1007/s10584-011-0045-5

Ford, J. D., & King, D. (2015). A framework for examining adaptation readiness. *Mitigation and Adaptation Strategies for Global Change*, *20*(4), 505–526. https://doi.org/10.1007/s11027-013-9505-8

Friend, R., & Moench, M. (2013). What is the purpose of urban climate resilience? Implications for addressing poverty and vulnerability. *Urban Climate*, *6*, 98–113. https://doi.org/10.1016/j.uclim.2013.09.002

Frölicher, T. L., Winton, M., & Sarmiento, J. L. (2014). Continued global warming after CO2 emissions stoppage. *Nature Climate Change*, *4*(1), 40–44. https://doi.org/10.1038/nclimate2060

Fry, M. (2017). *Glasgow: A history of the city*. Head of Zeus.

Fulop, J. (2007). Introduction to decision-making. In *Digital Decision-making* (pp. 13–32). https://doi.org/10.1007/978-1-84628-673-5_2

Fünfgeld, H., Lonsdale, K., & Bosomworth, K. (2019). Beyond the tools: supporting adaptation when organisational resources and capacities are in short supply. *Climatic Change*, *153*(4), 625–641. https://doi.org/10.1007/s10584-018-2238-7

Fung, A. (2006). Varieties of Participation in Complex Governance. *Public Administration Review*, *66*(May 2021), 66–75.

Füssel, H.M. (2007). Adaptation Planning for Climate Change : Concepts, Assessment Approaches and Key Lessons. *Sustainability Science*, (September 2007). https://doi.org/10.1007/s11625-007-0032-y

Füssel, H.-M. (2007). Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustainability Science*, *2*(2), 265–275.

https://doi.org/10.1007/s11625-007-0032-y

Füssel, H. M. (2007). Vulnerability: A generally applicable conceptual framework for climate change research. *Global Environmental Change*, *17*(2), 155–167. https://doi.org/10.1016/j.gloenvcha.2006.05.002

Füssel, H. M., & Klein, R. J. T. (2006). Climate change vulnerability assessments: An evolution of conceptual thinking. *Climatic Change*, *75*(3), 301–329. https://doi.org/10.1007/s10584-006-0329-3

Gawith, D., & Hodge, I. (2018). Moving beyond description to explore the empirics of adaptation constraints. *Ecological Indicators*, *95*(May), 907–916. https://doi.org/10.1016/j.ecolind.2018.08.022

GCC. (2010). *Glasgow City Council's Climate Change Strategy*. Retrieved from https://www.glasgow.gov.uk/councillorsandcommittees/viewSelectedDocument. asp?c=P62AFQ0GZLZ3Z3T1#:~:text=The aim of the Climate,ensure delivery from 2010 onwards.

GCC. (2016a). Our Resilient Glasgow. In *100 Resilient Cities*.

GCC. (2016b). *Our Resilient Glasgow A City Strategy*.

GCC. (2017). *Glasgow City Council Strategic Plan 2017-2022*.

GCC. (2020). History of the Office of Lord Provost. Retrieved January 8, 2020, from https://www.glasgow.gov.uk/index.aspx?articleid=16555

GCC. (2021). *Glasgow's Climate Plan*. Retrieved from https://www.glasgow.gov.uk/CHttpHandler.ashx?id=50623&p=0

Gencer, E. A. (2013). *The Interplay between Urban Development, Vulnerability, and Risk Management*. https://doi.org/10.1007/978-3-642-29470-9

Gergen, K. J., & Gergen, M. M. (2015). Social Construction and Research as Action. In *The SAGE Handbook of Action Research* (2nd Editio, pp. 159–171). https://doi.org/10.4135/9781848607934.n16

Ghahramani, Z. (1998). *Learning dynamic Bayesian networks*. https://doi.org/10.1007/BFb0053999

Gigerenzer, G., Gaissmaier, W., Kurz-Milcke, E., Schwartz, L. M., & Woloshin, S. (2007). Helping Doctors and Patients Make Sense of Health Statistics. *Psychological Science in the Public Interest*, *8*(2), 53–96. https://doi.org/10.1111/j.1539-6053.2008.00033.x

Giupponi, C., Mysiak, J., & Sgobbi, A. (2008). Participatory Modelling and Decision

Support for Natural Resources Management in Climate Change Research. *SSRN Electronic Journal*, (I). https://doi.org/10.2139/ssrn.1105109

Given, L. (2012). Semi-Structured Interview. In *The SAGE Encyclopedia of Qualitative Research Methods*. SAGE Publications.

Glasgow Convention Bureau. (2019). *People Make Glasgow Greener Strategy 2020-2023*.

Glencross, K., Warren, R., Eunson, J., & Mori, I. (2021). *Understanding the barriers to uptake of Property Flood Resilience ( PFR ) in Scotland Executive summary*. https://doi.org/http://dx.doi.org/10.7488/era/947

Goldszmidt, M. (1994). Probability. *AI M*, *15*(4), 63–66.

Gorddard, R., Colloff, M. J., Wise, R. M., Ware, D., & Dunlop, M. (2016). Values, rules and knowledge: Adaptation as change in the decision context. *Environmental Science & Policy*, *57*, 60–69. https://doi.org/10.1016/j.envsci.2015.12.004

Grahn, T., & Nyberg, L. (2017). Assessment of pluvial flood exposure and vulnerability of residential areas. *International Journal of Disaster Risk Reduction*, *21*(January), 367–375. https://doi.org/10.1016/j.ijdrr.2017.01.016

Greater London Authority. (2011). *Managing risks and increasing resilience*.

Grêt-Regamey, A., & Straub, D. (2006). Spatially explicit avalanche risk assessment linking Bayesian networks to a GIS. *Natural Hazards and Earth System Sciences*, *6*(6), 911–926. https://doi.org/10.5194/nhess-6-911-2006

Grint, K. (2010). Wicked problems and clumsy solutions: The role of leadership. *The New Public Leadership Challenge*, 169–186. https://doi.org/10.1057/9780230277953

Gunderson, L. H. (2000). Ecological Resilience-In Theory and Application. *Annual Review of Ecology and Systematics*, *31*(2000), 425–439.

Gutierrez, B. T., Plant, N. G., & Thieler, E. R. (2011). A Bayesian network to predict coastal vulnerability to sea level rise. *Journal of Geophysical Research: Earth Surface*, *116*(F2), 1–15. https://doi.org/10.1029/2010JF001891

Hackenbruch, J., Kunz-Plapp, T., Müller, S., & Schipper, J. (2017). Tailoring Climate Parameters to Information Needs for Local Adaptation to Climate Change. *Climate*, *5*(2), 25. https://doi.org/10.3390/cli5020025

Hallegatte, S., & Corfee-Morlot, J. (2011). Understanding climate change impacts, vulnerability and adaptation at city scale: an introduction. *Climatic Change*, *104*(1), 1–12. https://doi.org/10.1007/s10584-010-9981-8

Hanea, A. M., McBride, M. F., Burgman, M. A., & Wintle, B. C. (2018). Classical meets modern in the IDEA protocol for structured expert judgement. *Journal of Risk Research*, *21*(4), 417–433. https://doi.org/10.1080/13669877.2016.1215346

Hanlon, P., Walsh, D., & Whyte, B. (2006). *Let Glasgow Flourish - A comprehensive report on health and its determinants in Glasgow and West Central Scotland*.

Hansen, A., & Bi, P. (2017). Climate change adaptation: no one size fits all. *The Lancet Planetary Health*, *1*(9), e353–e354. https://doi.org/10.1016/S2542-5196(17)30160-2

Harpending, H. C., & Sobus, J. (1987). Sociopathy as an adaptation. *Ethology and Sociobiology*, *8*(SUPPL. 1), 63–72. https://doi.org/10.1016/0162-3095(87)90019-7

Hastings, A., Bailey, N., Bramley, G., Gannon, M., & Watkins, D. (2015). The Cost of the Cuts: The Impact on Local Government and Poorer Comunities. In *Joseph Rowntree Foundation Report*.

Head, B. W. (2014). Evidence, Uncertainty, and Wicked Problems in Climate Change Decision-making in Australia. *Environment and Planning C: Government and Policy*, *32*(4), 663–679. https://doi.org/10.1068/c1240

Heald, D., & Steel, D. (2018). The governance of public bodies in times of austerity. *The British Accounting Review*, *50*(2), 149–160. https://doi.org/10.1016/j.bar.2017.11.001

Heino, M. T. J., Vuorre, M., & Hankonen, N. (2018). *Bayesian evaluation of behavior change interventions : a brief introduction and a practical example*. *2850*. https://doi.org/10.1080/21642850.2018.1428102

Herbert, S. (2000). For ethnography. *Progress in Human Geography*, *24*(4), 550–568. https://doi.org/10.1191/030913200100189102

Herman, J. D., Reed, P. M., Zeff, H. B., & Characklis, G. W. (2015). How Should Robustness Be Defined for Water Systems Planning under Change? *Journal of Water Resources Planning and Management*, *141*(10), 04015012. https://doi.org/10.1061/(asce)wr.1943-5452.0000509

Hinkel, J., & Bisaro, A. (2015). A review and classification of analytical methods for climate change adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, *6*(2), 171–188. https://doi.org/10.1002/wcc.322

HM Treasury (HMT). (2022). The Green Book Central Government Guidance on Appraisal and Evaluation. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1063330/Green_Book_2022.pdf

Hodgetts, D., & Chamberlain, K. (2013). Analysing News Media. In *The SAGE Handbook of Qualitative Data Analysis* (pp. 380–394). Retrieved from http://dx.doi.org/10.4135/9781446282243

Hoegh-Guldberg O., Jacob D., Taylor M., Bindi M., Brown S., Camilloni I., Diedhiou A., D. R. et al. (Achlatis M. listed as contributing author). (2018). Chapter 3: Impacts of 1.5°C global warming on natural and human systems. In: Global Warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above preindustrial levels and related global greenhouse gas emission pathways [...]. In *Special Report, Intergovernmental Panel on Climate Change* (pp. 175–311).

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Houston, D., Werrity, A., Bassett, D., Geddes, A., Hoolachan, A., & McMillan, M. (2011). Pluvial (rain-related) flooding in urban areas: the invisible hazard. In *Joseph Rowntree Foundation*. Retrieved from http://www.jrf.org.uk/publications/pluvial-flooding-invisible-hazard

Houston, Donald, Werritty, A., & Bassett, D. (2011). *Pluvial (rain-related) flooding in urban areas: the invisible hazard*.

Howard, R. A., & Matheson, J. E. (2005). Influence Diagrams. *Decision Analysis*, *2*(3), 127–143. https://doi.org/10.1287/deca.1050.0020

Howarth, C., Lane, M., & Fankhauser, S. (2021). What next for local government climate emergency declarations? The gap between rhetoric and action. *Climatic Change*, *167*(3–4), 1–22. https://doi.org/10.1007/s10584-021-03147-4

Hügel, S., & Davies, A. R. (2020). Public participation, engagement, and climate change adaptation: A review of the research literature. *WIREs Climate Change*, *11*(4), 1–20. https://doi.org/10.1002/wcc.645

Hunt, A., & Watkiss, P. (2011a). Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, *104*(1), 13–49.

https://doi.org/10.1007/s10584-010-9975-6

Hunt, A., & Watkiss, P. (2011b). Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, *104*(1), 13–49. https://doi.org/10.1007/s10584-010-9975-6

Hunt, A., & Watkiss, P. (2011c). Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, *104*(1), 13–49. https://doi.org/10.1007/s10584-010-9975-6

Iles, V., & Sutherland, K. (2001). Organisational Change: A Review for Health Care Managers, Professionals and Researchers. In *Managing Change in the NHS*. London: NCCSDO.

IPCC. (2007). *Climate Change 2007: Synthesis Report*.

IPCC. (2014a). Annex II: Glossary. In S. . Mach, K.J., S. Planton, & C. von Stechow (Eds.), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 117-130.). Geneva, Switzerland.

IPCC. (2014b). Climate Change 2014 Part A: Global and Sectoral Aspects. In C. B. . Field, V. Barros, D. Dokken, K. J. Mach, M. D. Mastrandrea, M. Bilir, … Y. O. Ebi (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from Cambridge University Press, website: papers2://publication/uuid/B8BF5043-C873-4AFD-97F9-A630782E590D

IPCC. (2014c). Summary for Policymakers. In Intergovernmental Panel on Climate Change (Ed.), *Climate Change 2013 - The Physical Science Basis* (pp. 1–30). https://doi.org/10.1017/CBO9781107415324.004

IPCC. (2014d). Working Group II: Impacts, Adaptation and Vulnerability.

IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. https://doi.org/10.1002/9780470996621.ch50

Jakeman, A. J., Letcher, R. A., & Norton, J. P. (2006). Ten iterative steps in development and evaluation of environmental models. *Environmental Modelling*

*& Software*, *21*(5), 602–614. https://doi.org/10.1016/j.envsoft.2006.01.004

Janetos, A. C. (2020). Why is climate adaptation so important? What are the needs for additional research? *Climatic Change*, *161*(1), 171–176. https://doi.org/10.1007/s10584-019-02651-y

Janis, I., & Mann, L. (1977). *Decision-making: A Psychological Analysis of Conflict, Choice and Commitment*. New York, NY: The Free press - A Division of Macmillan Publishing Co, Inc.

Johansson, M. (2015). Data sources on small-scale disaster losses and response – A Swedish case study of extreme rainfalls 2000–2012. *International Journal of Disaster Risk Reduction*, *12*, 93–101. https://doi.org/10.1016/j.ijdrr.2014.12.004

Johnston, J. H., Driskell, J. E., & Salas, E. (1997). Vigilant and hypervigilant decision-making. *Journal of Applied Psychology*, *82*(4), 614–622. https://doi.org/10.1037/0021-9010.82.4.614

Jones, B. (1999). Bounded Rationality. *Annual Review Political Science*, *2*, 297–321. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/B9780080970868930125

Jones, R. N., Patwardhan, A., Cohen, S. J., Dessai, S., Lammel, A., Lempert, R. J., … Kumar, P. (2014). Foundations for Decision-making. In Christopher B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, & M. D. Mastrandrea (Eds.), *Climate Change 2014 Impacts, Adaptation, and Vulnerability* (pp. 195–228). https://doi.org/10.1017/CBO9781107415379.007

Karanam, A., Hayes, A. L., Kokel, H., Haas, D. M., Radivojac, P., & Natarajan, S. (2021). A Probabilistic Approach to Extract Qualitative Knowledge for Early Prediction of Gestational Diabetes. *Artificial Intelligence in Medicine*, (AIME 2021), 497–502. https://doi.org/10.1007/978-3-030-77211-6_59

Kates, R. W., Travis, W. R., & Wilbanks, T. J. (2012). Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences*, *109*(19), 7156–7161. https://doi.org/10.1073/pnas.1115521109

Kauffman, S. a. (1991). Antichaos and Adaptation complex systems tend toward self-organization. *Scientific American*, *265*(August), 78–85.

Keinan, G., Friedland, N., & Ben-porath, Y. (1987). Decision-making under Stress: Scanning of alternatives under physical threat. *Acta Psychologica*, *64*, 219–228.

Kelly (Letcher), R. A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., ElSawah, S., Hamilton, S. H., … Voinov, A. A. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software*, *47*, 159–181. https://doi.org/10.1016/j.envsoft.2013.05.005

Keogh, D. U., Apan, A., Mushtaq, S., King, D., & Thomas, M. (2011). Resilience, vulnerability and adaptive capacity of an inland rural town prone to flooding: A climate change adaptation case study of Charleville, Queensland, Australia. *Natural Hazards*, *59*(2), 699–723. https://doi.org/10.1007/s11069-011-9791-y

Khakzad, N., Khan, F., & Amyotte, P. (2011). Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches. *Reliability Engineering and System Safety*, *96*(8), 925–932. https://doi.org/10.1016/j.ress.2011.03.012

Kiem, A. S., Verdon-Kidd, D. C., & Austin, E. K. (2014). Bridging the gap between end user needs and science capability: Decision-making under uncertainty. *Climate Research*, *61*(1), 57–74. https://doi.org/10.3354/cr01243

King, D. A. (2004). Climate Change Science: Adapt, Mitigate, or Ignore? *Science*, *303*(5655), 176–177. https://doi.org/10.1126/science.1094329

King, N., & Brooks, J. (2018). Thematic Analysis in Organisational Research. In *The SAGE Handbook of Qualitative Business and Management Research Methods: Methods and Challenges* (pp. 219–236). https://doi.org/10.4135/9781526430236.n14

Kintrea, K. and Madgin, R. (eds. . (2019). *Transforming Glasgow: Beyond the Post-Industrial City*. Bristol: Policy Press.

Kirchhoff, C. J., Lemos, M. C., & Kalafatis, S. (2015). Narrowing the gap between climate science and adaptation action: The role of boundary chains. *Climate Risk Management*, *9*, 1–5. https://doi.org/10.1016/j.crm.2015.06.002

Kithiia, J., & Dowling, R. (2010). An integrated city-level planning process to address the impacts of climate change in Kenya: The case of Mombasa. *Cities*, *27*(6), 466–475. https://doi.org/10.1016/j.cities.2010.08.001

Klein, R. J. T. (2003). Adaptation to climate variability and change: What is optimal and appropriate? *Climate Change in the Mediterranean: Socio-Economic Perspectives of Impacts, Vulnerability and Adaptation*, (Cdm), 32–50.

https://doi.org/10.4337/9781781950258.00013

Klein, R. J. T., Adams, K. M., Dzebo, A., Davis, M., & Siebert, C. K. (2017). Advancing climate adaptation practices and solutions: Emerging research priorities. In *SEI working paper 2017-07*. Retrieved from https://link.springer.com/content/pdf/10.1007%2Fs10784-017-9357-x.pdf

Klein, R. J. T., Midgley, G. F., Preston, B. L., Alam, M., Berkhout, F. G. H., Dow, K., … Thomas, A. (2015). Adaptation opportunities, constraints, and limits. *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*, 899–944. https://doi.org/10.1017/CBO9781107415379.021

Klein, R. J. T., Nicholls, R. J., & Thomalla, F. (2003). Resilience to natural hazards: How useful is this concept? *Environmental Hazards*, *5*(1–2), 35–45. https://doi.org/10.1016/j.hazards.2004.02.001

Klein, R. J. T., Schipper, E. L. F., & Dessai, S. (2005). Integrating mitigation and adaptation into climate and development policy: Three research questions. *Environmental Science and Policy*, *8*(6), 579–588. https://doi.org/10.1016/j.envsci.2005.06.010

Klein, R. J., & Tol, R. S. J. (1997). Adaptation to climate change: options and technologies. In *Technical Paper for UNFCCC*.

Knopman, D., & Lempert, R. (2016). Urban responses to climate change. In *RAND Corporation*.

Kock, N. (2003). Action research: Lessons learned from a multi-iteration study of computer-mediated communication in groups. *IEEE Transactions on Professional Communication*, *46*(2), 105–128. https://doi.org/10.1109/TPC.2003.813164

Kok, K., & Pedde, S. (2016). *IMPRESSIONS - socio-economic scenarios*. Retrieved from http://www.impressions-project.eu

Konidari, P., & Mavrakis, D. (2006). Multi-criteria evaluation of climate policy interactions. *Journal of Multi-Criteria Decision Analysis*, *14*(1–3), 35–53. https://doi.org/10.1002/mcda.399

Kuang, D., & Liao, K. H. (2020). Learning from Floods: Linking flood experience and flood resilience. *Journal of Environmental Management*, *271*(February), 111025. https://doi.org/10.1016/j.jenvman.2020.111025

Kuipers, B. S., Higgs, M., Kickert, W., Tummers, L., Grandia, J., & Van Der Voet, J. (2014). The management of change in public organizations: A literature review.

*Public Administration*, *92*(1), 1–20. https://doi.org/10.1111/padm.12040

Kuyper, J., & Schroeder, H. (2018). The Evolution of the UNFCCC. *Annual Review of Environment and Resources*, *43*, 343–368. https://doi.org/https://doi.org/10.1146/annurev-environ- 102017-030119

Kwakkel, J. H. (2020). Is real options analysis fit for purpose in supporting climate adaptation planning and decision-making? *Wiley Interdisciplinary Reviews: Climate Change*, *11*(3), 1–8. https://doi.org/10.1002/wcc.638

Kwakkel, J. H., Walker, W. E., & Haasnoot, M. (2016). Coping with the wickedness of public policy problems: Approaches for decision-making under deep uncertainty. *Journal of Water Resources Planning and Management*, *142*(3), 1–5. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000626

Kwakkel, J., & Haasnoot, M. (2019). Supporting DMDU: A Taxonomy of Approaches and Tools. In *Decision-making under Deep Uncertainty: From Theory to Practice*. Springer.

Kwisthout, J., & Tel, G. (2006). Complexity results for enhanced qualitative probabilistic networks. *Proceedings of the 3rd European Workshop on Probabilistic Graphical Models, PGM 2006*, 171–178.

Kythreotis, A. P., & Bristow, G. I. (2016). The ‘resilience trap’: exploring the practical utility of resilience for climate change adaptation in UK city-regions. *Regional Studies*, *3404*(September), 1–12. https://doi.org/10.1080/00343404.2016.1200719

Lamb, W. F. ., Creutzig, F., & Callaghan, M. . (2019). Learning about urban climate solutions from case studies. *Nature Climate Change*, (9), 279–287. https://doi.org/https://doi.org/10.1038/s41558-019-0440-x

Lancaster, W., & Lancaster, J. (1982). Rational Decision-making. *JONA: The Journal of Nursing Administration*, *12*(9), 23–28. https://doi.org/10.1097/00005110-198209000-00007

Landauer, M., Juhola, S., & Klein, J. (2019). The role of scale in integrating climate change adaptation and mitigation in cities. *Journal of Environmental Planning and Management*, *62*(5), 741–765. https://doi.org/10.1080/09640568.2018.1430022

Laukkonen, J., Blanco, P. K., Lenhart, J., Keiner, M., Cavric, B., & Kinuthia-Njenga, C. (2009). Combining climate change adaptation and mitigation measures at the local level. *Habitat International*, *33*(3), 287–292.

https://doi.org/10.1016/j.habitatint.2008.10.003

Lee, S., Kang, J. E., Park, C. S., Yoon, D. K., & Yoon, S. (2020). Multi-risk assessment of heat waves under intensifying climate change using Bayesian Networks. *International Journal of Disaster Risk Reduction*, *50*(May), 101704. https://doi.org/10.1016/j.ijdrr.2020.101704

Lee, T. (2013). Global Cities and Transnational Climate Change Networks. *Global Environmental Politics*, *13*(1), 108–127.

Leggett, J. A. (2021). *Climate Change: Defining Adaptation and Resilience, with Implications for Policy*.

Lehmann, P., Brenck, M., Gebhardt, O., Schaller, S., & Süßbauer, E. (2015). Barriers and opportunities for urban adaptation planning: analytical framework and evidence from cities in Latin America and Germany. *Mitigation and Adaptation Strategies for Global Change*, *20*(1), 75–97. https://doi.org/10.1007/s11027-013-9480-0

Leichenko, R. (2011). Climate change and urban resilience. *Current Opinion in Environmental Sustainability*, *3*(3), 164–168. https://doi.org/10.1016/j.cosust.2010.12.014

Lemos, M. C., Kirchhoff, C. J., & Ramprasad, V. (2012). Narrowing the climate information usability gap. *Nature Climate Change*, *2*(11), 789–794. https://doi.org/10.1038/nclimate1614

Lempert, R. J. (2003). *Shaping the next one hundred years: new methods for quantitative, long-term policy analysis*. Retrieved from https://www.rand.org/content/dam/rand/pubs/monograph_reports/2007/MR1626.pdf

Lenski, R. (2017). What is adaptation by natural selection? Perspectives of an experimental microbiologist. *PLOS Genetics*, *13*(4), 457–474. https://doi.org/10.1106/2UU8-8JJD-UHRU-C14R

Lewin, K. (1948). Action research and minority problems. In *Resolving Social Conflict* (pp. 201–16). Harper and Row.

Lexis Nexis. (2021). Nexis Solutions: Empowering Performance. Retrieved August 26, 2021, from https://bis.lexisnexis.co.uk/

Lietz, P. (2010). Research into questionnaire design. *International Journal of Market Research*, *52*(2), 249–272. https://doi.org/10.2501/S147078530920120X

Lim, B., Spanger-siegfried, E., Burton, I., Malone, E. L., Huq, S., Spanger-S, & Iegfried, E. (2004). Adaptation Policy Frameworks for Climate Change : Developing Strategies, Policies and Measures. *Framework*, 263. https://doi.org/ISBN 0 521 61760 X paperback

Lindley, S., O'Neill, J., Kandeh, J., Lawson, N., Christian, R., & O'Neill, M. (2011). Climate change, justice and vulnerability. *Joseph Rowntree Foundation*, (November), 1–180. Retrieved from http://nationalfloodforum.org.uk/wp-content/uploads/JRF-climate-change-social-vulnerability-full.pdf

Liu, C., & Wellman, M. P. (1994). *Incremental Tradeoff Resolution in Qualitative Probabilistic Networks Incremental Tradeoff Resolution in QPNs*. 338–345.

Local Government Association. (2020). What is local government? Retrieved December 21, 2020, from https://www.local.gov.uk/about/what-local-government

Lonsdale, K. (2012). *Beyond tools : building learning organisations to adapt to a changing climate*. Final report, Victorian Centre for Climate Change Adaptation Research Visiting Fellowship. Available online at: http://www.vcccar.org.au/sites/default/files/publications/VCCCAR_Final_Report_Kate_Lonsdale_forweb_150713.pdf

Lonsdale, K. and Goldthorpe, M. 2012. Collaborative research for a changing climate: Learning from researchers and stakeholders in the ARCC programme. Adaptation and Resilience in a Changing Climate Coordination Network, UKCIP, Oxford.

Lorenz, S., Porter, J. J., & Dessai, S. (2019). Identifying and tracking key climate adaptation actors in the UK. *Regional Environmental Change*, *19*(7), 2125–2138. https://doi.org/10.1007/s10113-019-01551-2

Lourenço , T. C. (2015). *Changing climate, changing decisions, understanding climate adaptation decision-making and the way science supports it* (Universidade de Lisboa). Retrieved from http://alteracoesclimaticas.ics.ulisboa.pt/wp-content/teses/2015TiagoLourenco.pdf

Lourenço, T. C., Rovisco, A., & Groot, A. (2014). *Making Adaptation Decisions Under Uncertainty : Lessons from Theory and Practice*. https://doi.org/10.1007/978-3-319-04876-5

Luber, G., & Prudent, N. (2009). Climate change and human health. *Transactions of the American Clinical and Climatological Association*, *120*, 113–117.

Lynam, T. (2016). Exploring social representations of adapting to climate change using topic modeling and Bayesian networks. *Ecology and Society*, *21*(4), art16. https://doi.org/10.5751/ES-08778-210416

Maani, K. (2013). *Decision-making for climate change adaptation: a systems thinking approach*.

Maier, H. R., Guillaume, J. H. A., van Delden, H., Riddell, G. A., Haasnoot, M., & Kwakkel, J. H. (2016). An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling and Software*, *81*, 154–164. https://doi.org/10.1016/j.envsoft.2016.03.014

Majekodunmi, M., Emmanuel, R., & Jafry, T. (2020). A spatial exploration of deprivation and green infrastructure ecosystem services within Glasgow city. *Urban Forestry and Urban Greening*, *52*(August 2019), 126698. https://doi.org/10.1016/j.ufug.2020.126698

Mann, L., Burnett, P., Radford, M., & Ford, S. (1997). The Melbourne decision-making questionnaire: An instrument for measuring patterns for coping with decisional conflict. *Journal of Behavioral Decision-making*, *10*(1), 1–19. https://doi.org/10.1002/(SICI)1099-0771(199703)10:1<1::AID-BDM242>3.0.CO;2-X

Manson, S. M., Ratick, S. J., & Solow, A. R. (2002). Decision-making and uncertainty: Bayesian analysis of potential flood heights. *Geographical Analysis*, *34*(2), 112–129. https://doi.org/10.1353/geo.2002.0012

Marcot, B., Steventon, J., Sutherland, G., & McCann, R. (2006). Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. *Canadian Journal of Forest Research*, *36*, 3063–3074. https://doi.org/10.1139/X06-135

Marquez, D., Neil, M., & Fenton, N. E. (2007). A new Bayesian Network approach to Reliability modelling. *5th International Mathematical Methods in Reliability Conference*. Retrieved from http://www.dcs.qmw.ac.uk/~norman/papers/Improved DFT modelling using BNs_v1.pdf

Mart, C., Malik, A., Gerken, M., Bastomski, S., Rajasekaran, P., Burnstein, E., … Gourevitch, R. (2018). *A Midterm Monitoring and Evaluation Report of 100 Resilient Cities and the participation of*. (December).

Maskrey, S. (2016). *Supporting local flood risk decision-making using participatory* *modelling*. University of Nottingham.

Maskrey, S. A., Mount, N. J., Thorne, C. R., & Dryden, I. (2016). Participatory modelling for stakeholder involvement in the development of flood risk management intervention options. *Environmental Modelling and Software*, *82*, 275–294. https://doi.org/10.1016/j.envsoft.2016.04.027

McClymont, K., Morrison, D., Beevers, L., & Carmen, E. (2020). Flood resilience: a systematic review. *Journal of Environmental Planning and Management*, *63*(7), 1151–1176. https://doi.org/10.1080/09640568.2019.1641474

McDevitt, R., Giapponi, C., & Tromley, C. (2007). A model of ethical decision-making: The integration of process and content. *Journal of Business Ethics*, *73*(2), 219–229. https://doi.org/10.1007/s10551-006-9202-6

McDougald, D., Rice, S. A., Weichart, D., & Kjelleberg, S. (1998). Nonculturability: Adaptation or debilitation? *FEMS Microbiology Ecology*, *25*(1), 1–9. https://doi.org/10.1016/S0168-6496(97)00063-9

McEvoy, D; Lindley, S. ; Handley, J. (2006). *Adaptation and mitigation in urban areas : synergies and conflicts*. (December), 185–191.

McEvoy, D., Fünfgeld, H., & Bosomworth, K. (2013). Resilience and Climate Change Adaptation: The Importance of Framing. *Planning Practice and Research*, *28*(3), 280–293. https://doi.org/10.1080/02697459.2013.787710

McLachlan, S., Dube, K., Hitman, G. A., Fenton, N. E., & Kyrimi, E. (2020). Bayesian networks in healthcare: Distribution by medical condition. *Artificial Intelligence in Medicine*, *107*(April), 101912. https://doi.org/10.1016/j.artmed.2020.101912

McLeod, R. S., & Hopfe, C. J. (2013). Hygrothermal implications of low and zero energy standards for building envelope performance in the UK. *Journal of Building Performance Simulation*, *6*(5), 367–384. https://doi.org/10.1080/19401493.2012.762809

Measham, T. G., Preston, B. L., Smith, T. F., Brooke, C., Gorddard, R., Withycombe, G., & Morrison, C. (2011). *Adapting to climate change through local municipal planning : barriers and challenges*. 889–909. https://doi.org/10.1007/s11027-011-9301-2

Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, *147*, 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011

Meerow, S., & Stults, M. (2016). Comparing conceptualizations of urban climate resilience in theory and practice. *Sustainability (Switzerland)*, *8*(7), 1–16. https://doi.org/10.3390/su8070701

Mehryar, S., Sasson, I., & Surminski, S. (2022). Supporting urban adaptation to climate change: What role can resilience measurement tools play? *Urban Climate*, *41*(394), 101047. https://doi.org/10.1016/j.uclim.2021.101047

Meighan, M. (2013). *Glasgow: A History*. Amberley Publishing.

Melorose, J., Perroy, R., & Careas, S. (2015). Bayesian belief modeling of climate change impacts better informs regional adaptation options. *Statewide Agricultural Land Use Baseline 2015*, *1*. https://doi.org/10.1017/CBO9781107415324.004

Merritt, W. S., Patch, B., Reddy, V. R., & Syme, G. J. (2015). Modelling livelihoods and household resilience to droughts using Bayesian networks. *Environment, Development and Sustainability*, 315–346. https://doi.org/10.1007/s10668-015-9650-1

MetOffice. (2017). Weather warnings guide. Retrieved from https://www.metoffice.gov.uk/weather/guides/warnings

Met Office. (2019). Effects of climate change. Retrieved November 30, 2020, from 2019 website: https://www.metoffice.gov.uk/weather/climate-change/effects-of-climate-change

Metroeconomica. (2006). Climate Change Impacts and Adaptation: Quantify the Cost of Impacts and Adaptation. In *Report to Defra*. Retrieved from https://econadapt-library.eu/node/2024

Milne, K. M. G. (2015). Can sense-making tools inform adaptation policy? A practitioner's perspective. *Ecology and Society*, *20*(1), art66. https://doi.org/10.5751/ES-06791-200166

Mimura, N., Pulwarty, R. S., Duc, D. M., Elshinnawy, I., Redsteer, M. H., Huang, H. Q., … Kato, S. (2014). Adaptation planning and implementation. *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*, 869–898. https://doi.org/10.1017/CBO9781107415379.020

Moallemi, E. A., Zare, F., Reed, P. M., Elsawah, S., Ryan, M. J., & Bryan, B. A. (2020). Structuring and evaluating decision support processes to enhance the robustness of complex human–natural systems. *Environmental Modelling and Software*, *123*(July 2019), 104551. https://doi.org/10.1016/j.envsoft.2019.104551

Molina, J.-L., Pulido-Velázquez, D., García-Aróstegui, J. L., & Pulido-Velázquez, M. (2013). Dynamic Bayesian Networks as a Decision Support tool for assessing Climate Change impacts on highly stressed groundwater systems. *Journal of Hydrology*, *479*, 113–129. https://doi.org/10.1016/j.jhydrol.2012.11.038

Montanari, A. (1989). Barcelona and Glasgow, similarities and differences in the history of two port cities. *The Journal of European Economic History*, (May), 2003–2006.

Moore, N., & Gerhart, M. (2013). *Scenario planning for climate change adaptation*.

Morgan, Granger. ; Henrion, M. (1990). *Uncertainty: A Guide to Dealing with Uncertalnty In Quantitative Risk and Policy Analysis*. New York: Cambridge University Press.

Morgan, C., Foster, J. A., Poston, A., & Sharpe, T. R. (2017). Overheating in Scotland: contributing factors in occupied homes. *Building Research and Information*, *45*(1–2), 143–156. https://doi.org/10.1080/09613218.2017.1241472

Morgan, M G, Pitelka, L. F., & Shevliakova, E. (2001). Elicitation of expert judgments of climate change impacts on forest ecosystems. *Climatic Change*, *49*(3), 279–307. https://doi.org/10.1023/A:1010651300697

Morgan, M Granger. (2014). Use (and abuse) of expert elicitation in support of decision-making for public policy. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(20), 7176–7184. https://doi.org/10.1073/pnas.1319946111

Morgan, M Granger, Dowlatabadi, H., Henrion, M., Keith, D., Lempert, R., McBride, S., … Wilbanks, T. (2009). Best Practice Approaches for Communicating , and Incorporating Scientific Uncertainty in Climate Decision-making. *A Report by the Climate Change Science Program and the Subcommittee on Global Change Research*, (January), 94 pp. Retrieved from http://www.climatescience.gov/Library/sap/sap5-2/final-report/default.htm

Morris, A. H. (2018). Human cognitive limitations: Broad, consistent, clinical application of physiological principles will require decision support. *Annals of the American Thoracic Society*, *15*(3), S53–S56. https://doi.org/10.1513/AnnalsATS.201706-449KV

Moser, S. (2009). Making a difference on the ground: The challenge of demonstrating the effectiveness of decision support. *Climatic Change*, *95*(1–2), 11–21.

https://doi.org/10.1007/s10584-008-9539-1

Moser, S., & Ekstrom, J. A. (2010a). A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(51), 22026–22031. https://doi.org/10.1073/pnas.1007887107

Moser, S., & Ekstrom, J. A. (2010b). *A framework to diagnose barriers to climate change adaptation*. https://doi.org/10.1073/pnas.1007887107/-/DCSupplemental.www.pnas.org/cgi/doi/10.1073/pnas.1007887107

Moss, R. H., Meehl, G. A., Lemos, M. C., Smith, J. B., Arnold, J. R., Arnott, J. C., … Wilbanks, T. J. (2013). Hell and High Water: Practice-Relevant Adaptation Science. *Science*, *342*(6159), 696–698. https://doi.org/10.1126/science.1239569

Musango, J. K., & Peter, C. (2007). A Bayesian approach towards facilitating climate change adaptation research on the South African agricultural sector. *Agrekon*, *46*(2), 245–259. https://doi.org/10.1080/03031853.2007.9523770

Mustelin, J., Kuruppu, N., Kramer, A. M., Daron, J., de Bruin, K., & Noriega, A. G. (2013). Climate adaptation research for the next generation. *Climate and Development*, *5*(3), 189–193. https://doi.org/10.1080/17565529.2013.812953

Nachmany, M., Fankhauser, S., Setzer, J., & Averchenkova, A. (2017). Global trends in climate change legislation and litigation. In *Grantham Research Institute on Climate Change and the Environment*.

Nadkarni, S., & Shenoy, P. P. (2004). A causal mapping approach to constructing Bayesian networks. *Decision Support Systems*, *38*(2), 259–281. https://doi.org/10.1016/S0167-9236(03)00095-2

Nakicenovic, N. et al. (2000). *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Ed.). Retrieved from http://www.grida.no/climate/ipcc/emission/index.htm

Nalau, J., Preston, B. L., & Maloney, M. C. (2015). Is adaptation a local responsibility? *Environmental Science and Policy*, *48*, 89–98. https://doi.org/10.1016/j.envsci.2014.12.011

Nalau, J., Torabi, E., Edwards, N., Howes, M., & Morgan, E. (2021). A critical exploration of adaptation heuristics. *Climate Risk Management*, *32*(March), 100292. https://doi.org/10.1016/j.crm.2021.100292

NASA. (2019). The Atmosphere: Getting a Handle on Carbon Dioxide. Retrieved September 3, 2020, from Global climate change: vital signs of the planet website: https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/

National Records of Scotland. (2021). Glasgow City Council Area Profile. Retrieved September 1, 2021, from https://www.nrscotland.gov.uk/files/statistics/council-area-data-sheets/glasgow-city-council-profile.html#:~:text=Population Estimates,-Last updated%3A June&text=On 30 June 2020%2C the,of Scotland increased by 0.0%25.&text=Glasgow City had the highest,32

National Research Council. (2009). Informing Decisions in a Changing Climate. In *Informing Decisions in a Changing Climate*. https://doi.org/10.17226/12626

Naylor, L., Murtagh, E., & Kippen, H. (2019). Our "Dear Green Place": Glasgow's Transformation from industrial powerhouse to sustainable city. In *Transforming Glasgow* (pp. 257–278).

New York City Panel on Climate Change; (2019). New York City Panel on Climate Change 2019 Report Executive Summary. *Annals of the New York Academy of Sciences*, *1439*(1), 11–21. https://doi.org/10.1111/nyas.14008

New York City Panel on Climate Change. (2010). Executive summary of climate change adaptation in New york city: Building a Risk management response. *Annals of the New York Academy of Sciences*, *1196*, 7–11. https://doi.org/10.1111/j.1749-6632.2009.05398.x

Newman, G., Dongying, L., Rui, Z., & Dingding, R. (2019). Resilience through Regeneration: The economics of repurposing vacant land with green infrastructure. *Lands Arch Front*, *6*(6), 10–23. https://doi.org/10.15302/J-LAF-20180602.Resilience

Noble, I. R., Huq, S., Anokhin, Y. A., Carmin, J. A., Goudou, D., Lansigan, F. P., … Chu, E. (2014). Adaptation needs and options. *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*, 833–868. https://doi.org/10.1017/CBO9781107415379.019

Nojavan A., F., Qian, S. S., & Stow, C. A. (2017). Comparative analysis of discretization methods in Bayesian networks. *Environmental Modelling and Software*, *87*, 64–71. https://doi.org/10.1016/j.envsoft.2016.10.007

Nordgren, J., Stults, M., & Meerow, S. (2016). Supporting local climate change adaptation: Where we are and where we need to go. *Environmental Science and Policy*, *66*, 344–352. https://doi.org/10.1016/j.envsci.2016.05.006

O'Brien, M. J. O., & Holland, T. D. (1992). The Role of Adaptation in Archaeological Explanation. *American Antiquity*, *57*(1), 36–59.

O'Brien, R. (1998). An overview of the methodological approach of action Research. Faculty of Information Studies. *University of Toronto*, 1–15. Retrieved from http://www.web.ca/~robrien/papers/arfinal.html

O'Hagan, A. (2019). Expert Knowledge Elicitation: Subjective but Scientific. *American Statistician*, *73*(sup1), 69–81. https://doi.org/10.1080/00031305.2018.1518265

O'Hagan, A., Buck, C., Daneshkah, A., Eiser, R., Garthwaite, P., Jenkinson, D., … Rakow, T. (2006). *Uncertain Judgements : Elic-iting Expert Probabilities Uncertain Judgements :* https://doi.org/10.1002/0470033312

O'Neill, S., & Tett, S. (2019). *Mapping Future Scottish Heatwave Extremes : Report for Climate Ready Clyde*. (September), 1–24.

O'Sullivan, J. J., Bradford, R. A., Bonaiuto, M., De Dominicis, S., Rotko, P., Aaltonen, J., … Langan, S. J. (2012). Enhancing flood resilience through improved risk communications. *Natural Hazards and Earth System Science*, *12*(7), 2271–2282. https://doi.org/10.5194/nhess-12-2271-2012

Oberlack, C. (2017). Diagnosing institutional barriers and opportunities for adaptation to climate change. *Mitigation and Adaptation Strategies for Global Change*, *22*(5), 805–838. https://doi.org/10.1007/s11027-015-9699-z

Oberlack, C., & Neumarker, B. (2013). *A diagnostic approach to the institutional analysis of climate adaptation*.

OECD. (2003). The definition and selection of key competencies - Executive summary. *DeSeCo*, 1–20. https://doi.org/10.1080/2159676X.2012.712997

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B., … Hsiang, S. (2015). Emergent risks and key vulnerabilities. *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*, 1039–1100. https://doi.org/10.1017/CBO9781107415379.024

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B., & Takahashi, K. (2014). IPCC-WGII-AR5-19. Emergent Risks and Key Vulnerabilities. In and L. L. W. (eds. )]. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea (Ed.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1039–1099). https://doi.org/10.1017/CBO9781107415379

Orlove, B. (2009). The past, the present and some possible futures of adaptation. In *Adapting to Climate Change: Thresholds, Values, Governance* (pp. 129–163).

Orlove, B., Shwom, R., Markowitz, E., & Cheong, S. (2020). *Climate Decision-Making*.

Ostrom, E. (2009). Special Section : Special Section : *Science*, *325*(July), 419–422.

Owusu, S., Wright, G., & Arthur, S. (2015). Public attitudes towards flooding and property-level flood protection measures. *Natural Hazards*, *77*(3), 1963–1978. https://doi.org/10.1007/s11069-015-1686-x

Özesmi, U., & Özesmi, S. L. (2004). *Ecological models based on people ' s knowledge : a multi-step fuzzy cognitive mapping approach*. *176*, 43–64. https://doi.org/10.1016/j.ecolmodel.2003.10.027

Pacione, M. (1979). Housing policies in Glasgow since 1880. *Geographical Review*, *69*(4), 395–412. https://doi.org/10.2307/214803

Palutikof, J. P., Street, R. B., & Gardiner, E. P. (2019). Decision support platforms for climate change adaptation: an overview and introduction. *Climatic Change*, *153*(4), 459–476. https://doi.org/10.1007/s10584-019-02445-2

Park, S. E., Marshall, N. A., Jakku, E., Dowd, A. M., Howden, S. M., Mendham, E., & Fleming, A. (2012). Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change*, *22*(1), 115–126. https://doi.org/10.1016/j.gloenvcha.2011.10.003

Parsons, S. (1995). Refining reasoning in qualitative probabilistic networks. *Proceedings of the Eleventh Conference on Uncertainty in Artificial Intelligence*, 427–434. Retrieved from http://dblp.uni-trier.de/db/conf/uai/uai1995.html#Parsons95

Parsons, S. (2004). On precise and correct qualitative probabilistic inference. *International Journal of Approximate Reasoning*, *35*(2), 111–135. https://doi.org/10.1016/S0888-613X(03)00073-2

Patterson, J., de Voogt, D. L., & Sapiains, R. (2019). Beyond inputs and outputs: Process-oriented explanation of institutional change in climate adaptation governance. *Environmental Policy and Governance*, *29*(5), 360–375. https://doi.org/10.1002/eet.1865

Patwardhan, A., Downing, T., Leary, N., & Wilbanks, T. (2009). Towards an integrated agenda for adaptation research: theory, practice and policy. Strategy paper. *Current Opinion in Environmental Sustainability*, *1*(2), 219–225. https://doi.org/10.1016/j.cosust.2009.10.010

Pearl, J. (1988). *Probabilistic Reasoning in Intelligent Systems*. San Mateo, CA: Morgan Kaufmann.

Pedde, S., Harrison, P. A., Holman, I. P., Powney, G. D., Lofts, S., Schmucki, R., … Bullock, J. M. (2021). Enriching the Shared Socioeconomic Pathways to co-create consistent multi-sector scenarios for the UK. *Science of the Total Environment*, *756*, 143172. https://doi.org/10.1016/j.scitotenv.2020.143172

Pelling, M. (2011). Pelling to Climate Change: From resilience to transformation. In *Routledge London 203*.

Pelling, M., Brien, K. O., & Matyas, D. (2015). *Adaptation and transformation*. (December 2014), 113–127. https://doi.org/10.1007/s10584-014-1303-0

Pelling, M., & Manuel-Navarrete, D. (2011). From resilience to transformation: The adaptive cycle in two Mexican urban centers. *Ecology and Society*, *16*(2). https://doi.org/10.5751/ES-04038-160211

Penning-Rowsell, E. C. (2019). Flood insurance in Scotland: a cause for serious concern. *Scottish Geographical Journal*, *135*(1–2), 33–45. https://doi.org/10.1080/14702541.2019.1572918

Pettigrew, A. M. (1990). Longitudinal Field Research on Change: Theory and Practice. *Organization Science*, *1*(3), 267–292. https://doi.org/10.1287/orsc.1.3.267

Phan, T. D., Smart, J. C. R., Stewart-Koster, B., Sahin, O., Hadwen, W. L., Dinh, L. T., … Capon, S. J. (2019). Applications of bayesian networks as decision support tools for water resource management under climate change and socio-economic stressors: A critical appraisal. *Water (Switzerland)*, *11*(12). https://doi.org/10.3390/W11122642

Phillips-Wren, G., Mora, M., & Forgionne, G. (2011). *Assessing Today: Determining the Decision Value of Decision Support Systems*. (2002), 203–220. https://doi.org/10.1007/978-1-4419-6181-5_11

Pitchforth, J., Wu, P., & Mengersen, K. (2014). *Applying a Validation Framework to a*

*Working Airport Terminal Model*. https://doi.org/10.1016/j.eswa.2014.01.013

Pitt, M. (2008). *Learning lessons from the 2007 floods - Full Report*.

Policy Connect. (2021). UK Climate Policy Dashboard. Retrieved October 14, 2021, from https://www.policyconnect.org.uk/sustainability/climate-policy-dashboard

Pollino, C. A. ., & Hart, B. . (2008). Developing Bayesian network models within a risk assessment framework. *4th Biennial Meeting of International Congress on Environmental Modelling and Software: Integrating Sciences and Information Technology for Environmental Assessment and Decision-making*, *1*, 372–379. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84858320313&partnerID=40&md5=a89142353ce99d4c4909108f9b6b2251

Pollino, C. a., & Henderson, C. (2010). Bayesian networks : A guide for their application in natural resource. In *Landscape Logic Technical Report*. Retrieved from www.landscapelogic.org.au

Pollitt, C. (2015). Wickedness will not wait: climate change and public management research. *Public Money and Management*, *35*(3), 181–186. https://doi.org/10.1080/09540962.2015.1027490

Poundstone, W. (2019). *How to Predict Everything: The Forumula Transforming What We Know About Life and the Universe*. OneWorld Publications.

Power, K., England, K., Hoermann, B., Toplis, C., & Henderson, M. (2018). *Adaptation actions in Cities what works?* (August), 83. Retrieved from https://www.theccc.org.uk/wp-content/uploads/2018/11/Adaptation-actions-in-cities-what-works-final.pdf

Pregnolato, M., & Dawson, D. A. (2018). Adaptation investments for transport resilience: Trends and recommendations. *International Journal of Safety and Security Engineering*, *8*(4), 515–527. https://doi.org/10.2495/SAFE-V8-N4-515-527

Preston, B. L., Dow, K., & Berkhout, F. (2013). The climate adaptation frontier. *Sustainability (Switzerland)*, *5*(3), 1011–1035. https://doi.org/10.3390/su5031011

Preston, B. L., Maloney, M., Thomsen, D., Smith, T., Mangoyana, R., & Conlon, B. (2013). *A Multi-Criteria Analysis of Coastal Adaptation Options for Local Government*. https://doi.org/10.13140/RG.2.1.1695.4002

Pruneau, D., Kerry, J., Blain, S., Evichnevetski, E., Deguire, P., Barbier, P. Y., … Lang, M. (2013). Competencies demonstrated by municipal employees during adaptation to climate change: A pilot study. *Journal of Environmental Education*, *44*(4), 217–231. https://doi.org/10.1080/00958964.2012.759521

Pruyt, E. (2006). What is System Dynamics? A Paradigmatic Inquiry. *Proceedings of the 24th International Conference of the System Dynamics Society*, 102–103.

Pyke, C. R., Bierwagen, B. G., Furlow, J., Gamble, J., Johnson, T., Julius, S., & West, J. (2007). *A decision inventory approach for improving decision support for climate change impact assessment and adaptation*. *10*, 610–621. https://doi.org/10.1016/j.envsci.2007.05.001

Rabionet, S. E. (2011). How I learned to design and conduct semi-structured interviews: An ongoing and continuous journey. *Qualitative Report*, *16*(2), 563–566.

Rahmstorf, S. (2008). Anthropogenic climate change: Revisiting the facts. *Global Warming: Looking beyond Kyoto*, 34–53.

Ranger, N, Millner, A., Dietz, S., Fankhauser, S., Lopez, A., & Ruta, G. (2010). Adaptation in the UK: a decision-making process. *Grantham/CCCEP Policy Brief*, (September).

Ranger, Nicola;, Lopez, A., & Fankhauser, S. (2010). *Adaptation in the UK : a decision-making process*.

Ranger, Nicola;, Lopez, A., Fankhauser, S., & Rupta, G. (2010). *Adaptation in the UK : a decision-making process*.

Ravetz, J., & Funtowicz, S. (1991). *Uncertainty and Quality in Knowledge for Policy*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Reason, P., & Bradbury, H. (2008). *The SAGE Handbook of Action Research* (1st Editio). https://doi.org/10.4135/9781848607934

Reisinger, A., Howden, M., Vera, C., Garschagen, M., Hurlbert, M., Kreibiehl, S., … Ranasinghe, R. (2020). The concept of risk in the IPCC Sixth Assessment Report: a summary of cross-working group discussions. *Intergovernmental Panel on Climate Change, Geneva, Switzerland. Pp15*, (September), 15.

Renooij, S. (2001). *Qualitative approaches to quantifying probabilistic networks*. Retrieved from http://dspace.library.uu.nl/handle/1874/858

Renooij, Silja, & Gaag, L. Van Der. (1998). Decision-making in Qualitative Influence Diagrams. *FLAIRS Conference*, (1990), 1–10. Retrieved from http://www.aaai.org/Papers/FLAIRS/1998/FLAIRS98-079.pdf

Revi, A., Satterthwaite, D. E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R., Pelling, M., … Solecki, W. (2014). Urban areas. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 535–612.

Richards, R., Sanó, M., Roiko, A., Carter, R. W., Bussey, M., Matthews, J., & Smith, T. F. (2013a). Bayesian belief modeling of climate change impacts for informing regional adaptation options. *Environmental Modelling and Software*, *44*, 113–121. https://doi.org/10.1016/j.envsoft.2012.07.008

Richards, R., Sanó, M., Roiko, A., Carter, R. W., Bussey, M., Matthews, J., & Smith, T. F. (2013b). Bayesian belief modeling of climate change impacts for informing regional adaptation options. *Environmental Modelling & Software*, *44*, 113–121. https://doi.org/10.1016/j.envsoft.2012.07.008

Richards, R., Sanó, M., Roiko, A., Carter, R. W., Bussey, M., Matthews, J., & Smith, T. F. (2013c). Bayesian belief modeling of climate change impacts for informing regional adaptation options. *Environmental Modelling & Software*, *44*(July), 113–121. https://doi.org/10.1016/j.envsoft.2012.07.008

Richards, R., Sanó, M., Roiko, A., Carter, R. W., Bussey, M., Matthews, J., & Smith, T. F. (2013d). Bayesian belief modeling of climate change impacts for informing regional adaptation options. *Environmental Modelling and Software*, *44*(March), 113–121. https://doi.org/10.1016/j.envsoft.2012.07.008

Richardson, G. P. (1986). Problems with causal-loop diagrams. *System Dynamics Review*, *2*(2), 158–170. https://doi.org/10.1002/sdr.4260020207

Rickards, L., Wiseman, J., & Kashima, Y. (2014). Barriers to effective climate change mitigation: The case of senior government and business decision makers. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(6), 753–773. https://doi.org/10.1002/wcc.305

Rittel, H. & Webber, M. (1973). Dillemas in General Theory of Planning. *Policy Sciences*, *4*, 155–169.

Rittel,H, &Webber,M.(1973). Rittel_and_Webber_1973_Planning_Problems_Are_Wicked_Problems.Pdf. *Policy Sciences*, Vol. 4, pp. 155–169.

Rittel, Horst, & Webber, M. (1973). Dilemmas in a General Theory of Planning. *Policy*

*Sciences*, *4*, 155–169. https://doi.org/10.1080/01636609209550084

Rockefeller Foundation. (2017). 100 Resilient Cities. Retrieved from https://www.rockefellerfoundation.org/100-resilient-cities/

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., … Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °c. *Nature*, *534*(7609), 631–639. https://doi.org/10.1038/nature18307

Roggero, M., Bisaro, A., & Villamayor-Tomas, S. (2018). Institutions in the climate adaptation literature: A systematic literature review through the lens of the Institutional Analysis and Development framework. *Journal of Institutional Economics*, *14*(3), 423–448. https://doi.org/10.1017/S1744137417000376

Roiko, A., Mangoyana, R. B., McFallan, S., Carter, R. W. (Bill), Oliver, J., & Smith, T. F. (2012). Socio-economic trends and climate change adaptation: the case of South East Queensland. *Australasian Journal of Environmental Management*, *19*(1), 35–50. https://doi.org/10.1080/14486563.2011.646754

Rosenzweig, B. R., McPhillips, L., Chang, H., Cheng, C., Welty, C., Matsler, M., … Davidson, C. I. (2018). Pluvial flood risk and opportunities for resilience. *Wiley Interdisciplinary Reviews: Water*, *5*(6), 1–18. https://doi.org/10.1002/wat2.1302

Rosenzweig, Cynthia;, & Horton, R. M. (2013). *Priorities on Vulnerability, Impacts, and Adaptation*. Retrieved from http://www.unep.org/provia/RESOURCES/Publications/tabid/55299/Default.aspx

Rosenzweig, Cynthia, & Solecki, W. (2010). New York City adaptation in context. *Annals of the New York Academy of Sciences*, *1196*, 19–28. https://doi.org/10.1111/j.1749-6632.2009.05308.x

Rosenzweig, Cynthia, Solecki, W., Hammer, S. a, & Mehrotra, S. (2010). Cities lead the way in climate-change action. *Nature*, *467*(7318), 909–911. https://doi.org/10.1038/467909a

Rosenzweig, Cynthia, Solecki, W., Romero-Lankao, O., Mehrota, S., Dhakal, S., Bowman, T., & Ibrahim, S. (2015). *Climate Change and Cities. Second Assesment Report of the Urban Climate Change Research Network.* Retrieved from http://www.unhabitat.org/pmss/Publications.aspx?page=ByTheme&categoryID=550

Rotterdam Climate Initiative. (2013). *Rotterdam: Climate Change Adaptation Strategy*. 1–70. Retrieved from http://www.rotterdamclimateinitiative.nl/documents/Documenten/20121210_RAS_EN_lr_versie_4.pdf

Russel, D., Castellari, S., Capriolo, A., Dessai, S., Hildén, M., Jensen, A., … Tröltzsch, J. (2020). Policy coordination for national climate change adaptation in Europe: All process, but little power. *Sustainability (Switzerland)*, *12*(13), 1–18. https://doi.org/10.3390/su12135393

Ryan, P. C., & Stewart, M. G. (2017). Cost-benefit analysis of climate change adaptation for power pole networks. *Climatic Change*, *143*(3–4), 519–533. https://doi.org/10.1007/s10584-017-2000-6

Sahin, O., Richards, R., & Sano, M. (2013). Integrated modelling approach for climate change adaptation: The case of surf life saving Australia. *Proceedings - 20th International Congress on Modelling and Simulation, MODSIM 2013*, (December), 1749–1755. https://doi.org/10.36334/modsim.2013.h6.sahin

Sanford, A. D., & Moosa, I. A. (2012). A Bayesian network structure for operational risk modelling in structured finance operations. *Journal of the Operational Research Society*, *63*(4), 431–444. https://doi.org/10.1057/jors.2011.7

Sanò, M, Richards, R., Sahin, O., & Sherker, S. (2013). Adapt between the flags. In *NCCARD Synthesis and Integrative Research Final Report*. Retrieved from https://www.nccarf.edu.au/sites/default/files/attached_files_publications/Sano_2013_Adapt_between_the_flags_SLA.pdf

Sanò, Marcello, Richards, R., & Medina, R. (2014). A participatory approach for system conceptualization and analysis applied to coastal management in Egypt. *Environmental Modelling and Software*, *54*, 142–152. https://doi.org/10.1016/j.envsoft.2013.12.009

Satterthwaite, D., & Dodman, D. (2013). Towards resilience and transformation for cities within a finite planet. *Environment and Urbanization*, *25*(2), 291–298. https://doi.org/10.1177/0956247813501421

Sayers, P. B., Horritt, M., Penning-Rowsell, E. C., & Fieth, J. (2017). *Present and future flood vulnerability, risk and disadvantage - A UK assessment - Appendix B - Neighbourhood Flood Vulnerability Index*. (June), 20.

Sayers, P., & Meadowcroft, I. (2005). RASP - A hierarchy of risk-based methods and their application. *40th Defra Flood and Coastal Management Conference*, (July), 1–15.

Schneider, S. H. (1988). Greenhouse Effect : Science and Policy. *Science Research Articles*, *243*(7), 771–779.

Schum, D. A. (2001). Bayesian Theory: History of Applications. *International Encyclopedia of the Social & Behavioral Sciences*, 1056–1060. https://doi.org/10.1016/B0-08-043076-7/00625-2

Scottish Government. (2015). *Mapping Flood Disadvantage in Scotland 2015 : Main Report*.

Scottish Government. (2019a). Action to address climate emergency. Retrieved May 21, 2021, from https://www.gov.scot/news/action-to-address-climate-emergency/

Scottish Government. (2019b). *Climate Ready Scotland : Second Scottish Climate Change*. (September).

Scottish Government. (2020a). Local government. Retrieved October 13, 2021, from https://www.gov.scot/policies/local-government/

Scottish Government. (2020b). Scotland's leadership on climate change underlined. Retrieved from https://www.gov.scot/news/scotlands-leadership-on-climate-change-underlined/

Scottish Government. (2020c). *The Scottish Index of Multiple Deprivation (SIMD). [Online]*. 1–20. Retrieved from http://www.isdscotland.org/Products-and-Services/GPD-Support/Deprivation/SIMD/

Scottish Poetry Library. (2021). What the Clyde said, after COP26 by Kathleen Jamie. Retrieved January 3, 2022, from https://www.scottishpoetrylibrary.org.uk/poem/what-the-clyde-said-after-cop26/

Sen, P. (2016). Application of ANN in Six Sigma for CO modelling and energy efficiency of blast furnace: a case study of an Indian pig iron manufacturing organisation. *International Journal of Six Sigma and Competitive Advantage*, *9*(2-3–4), 109–125. https://doi.org/10.1504/IJSSCA.2015.074957

SEPA. (2015). Flood Risk Management Strategy Clyde and Loch Lomond. *SEPA Report*, 11. Retrieved from http://apps.sepa.org.uk/FRMStrategies/pdf/lpd/LPD_11_Full.pdf

SEPA. (2019). Climate change allowances for flood risk assessment in land use planning. *Sepa*, 19. Retrieved from https://www.sepa.org.uk/media/426913/lups_cc1.pdf

Sharma, J., & Ravindranath, N. H. (2019). Applying IPCC 2014 framework for hazard-specific vulnerability assessment under climate change. *Environmental Research Communications*, *1*(5), 051004. https://doi.org/10.1088/2515-7620/ab24ed

Shepherd, N. G., & Rudd, J. M. (2014). The influence of context on the strategic decision-making process: A review of the literature. *International Journal of Management Reviews*, *16*(3), 340–364. https://doi.org/10.1111/ijmr.12023

Shi, R., Hobbs, B. F., & Jiang, H. (2019). When can decision analysis improve climate adaptation planning? Two procedures to match analysis approaches with adaptation problems. *Climatic Change*, *157*(3–4), 611–630. https://doi.org/10.1007/s10584-019-02579-3

Siders, A. R., & Pierce, A. L. (2021). Deciding how to make climate change adaptation decisions. *Current Opinion in Environmental Sustainability*, *52*, 1–8. https://doi.org/10.1016/j.cosust.2021.03.017

Simonet, G., & Leseur, A. (2019). Barriers and drivers to adaptation to climate change—a field study of ten French local authorities. *Climatic Change*, *155*(4), 621–637. https://doi.org/10.1007/s10584-019-02484-9

Skea, J., & Nishioka, S. (2008). Policies and practices for a low-carbon society. *Climate Policy*, *8*(2008), S5–S16. https://doi.org/10.3763/cpol.2008.0487

Skourtos, M., Tourkolias, C., Damigos, D., Kontogianni, A., Harrison, P. A., & Berry, P. (2014). Incorporating cross-sectoral effects into analysis of the cost-effectiveness of climate change adaptation measures. *Climatic Change*, *128*(3–4), 307–321. https://doi.org/10.1007/s10584-014-1168-2

Smit, B., Burton, I., Klein, R., & Street, R. (1999). The Science of Adaptation: A Framework for Assessment. *Mitigation and Adaptation Strategies for Global Change 4*, *4*, 199–213. https://doi.org/https://doi.org/10.1023/A:1009652531101

Smit, B., Burton, I., Klein, R. J. T., & Wandel, J. (2000). An anatomy of adaptation. *Climatic Change*, *45*, 223–251.

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, *16*(3), 282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008

Smith, M. S., Horrocks, L., Harvey, A., & Hamilton, C. (2011). Rethinking adaptation for a 4°C world. *Philosophical Transactions of the Royal Society A: Mathematical,* *Physical and Engineering Sciences*, *369*(1934), 196–216. https://doi.org/10.1098/rsta.2010.0277

SMR. (2018). Smart Mature Resilience - For More Resilient Cities in Europe. Retrieved December 27, 2021, from https://smr-project.eu/home/

Snell, M. (2011). Basic principles of cost — benefit analysis. *Cost-Benefit Analysis: A Practical Guide*, *1*, 1–12.

Solecki, W., Leichenko, R., & O'Brien, K. (2011). Climate change adaptation strategies and disaster risk reduction in cities: Connections, contentions, and synergies. *Current Opinion in Environmental Sustainability*, *3*(3), 135–141. https://doi.org/10.1016/j.cosust.2011.03.001

Solomon, S., Daniel, J. S., Sanford, T. J., Murphy, D. M., Plattner, G. K., Knutti, R., & Friedlingstein, P. (2010). Persistence of climate changes due to a range of greenhouse gases. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(43), 18354–18359. https://doi.org/10.1073/pnas.1006282107

Sperotto, A., Molina, J. L., Torresan, S., Critto, A., & Marcomini, A. (2017). Reviewing Bayesian Networks potentials for climate change impacts assessment and management: A multi-risk perspective. *Journal of Environmental Management*, *202*, 320–331. https://doi.org/10.1016/j.jenvman.2017.07.044

Spetzler, C. S., & Stael von Holstein, C. A. S. (1975). Probability Encoding in Decision Analysis. *Management Science*, *22*(3), 340–358. https://doi.org/10.1287/mnsc.22.3.340

Spiegelhalter, S. L. Lauritzen, D. J. (1988). Local Computations with Probabilities on Graphical Structures and Their Application to Expert Systems. *Journal of the Royal Statistical Society. Series B (Methodological)*, *50*(2), 157–224.

Sprenger, J., & Hartmann, S. (2019). Bayesian Philosophy of Science. *Bayesian Philosophy of Science*. https://doi.org/10.1093/oso/9780199672110.001.0001

Star, J., Rowland, E. L., Black, M. E., Enquist, C. A. F., Garfin, G., Hoffman, C. H., … Waple, A. M. (2016). Supporting adaptation decisions through scenario planning: Enabling the effective use of multiple methods. *Climate Risk Management*, *13*, 88–94. https://doi.org/10.1016/j.crm.2016.08.001

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., … Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene.

*Proceedings of the National Academy of Sciences of the United States of America*, *115*(33), 8252–8259. https://doi.org/10.1073/pnas.1810141115

Stetler, C. B., Ritchie, J., Rycroft-Malone, J., Schultz, A., & Charns, M. (2007). Improving quality of care through routine, successful implementation of evidence-based practice at the bedside: An organizational case study protocol using the Pettigrew and Whipp model of strategic change. *Implementation Science*, *2*(1), 1–13. https://doi.org/10.1186/1748-5908-2-3

Stewart, M. G., Wang, X., & Willgoose, G. R. (2014). Direct and Indirect Cost-and-Benefit Assessment of Climate Adaptation Strategies for Housing for Extreme Wind Events in Queensland. *Natural Hazards Review*, *15*(4), 04014008. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000136

Stojadinovic, A., & Felix. (2010). Development of a Bayesian model to estimate health care outcomes in the severely wounded. *Journal of Multidisciplinary Healthcare*, 125. https://doi.org/10.2147/jmdh.s11537

Stott, P. (2016). How climate change affects extreme weather events. *Science*, *352*(6293), 1517–1518. https://doi.org/10.1126/science.aaf7271

Street, R. B., Pringle, P., Lourenço, T. C., & Nicolletti, M. (2019). Transferability of decision-support tools. *Climatic Change*, *153*(4), 523–538. https://doi.org/10.1007/s10584-018-2263-6

Stults, M., Nordgren, J., Meerow, S., Ongun, M., Jacobson, R., & Hamilton, C. (2015). Assessing the climate adaptation resource and service landscape. In *Living with Climate Change: How Communities Are Surviving and Thriving in a Changing Climate* (p. 285). CRC Press Baca Raton, FL.

Styczynski, A., Wolf, J., Tah, S., & Bose, A. (2014). When decision-making processes fail: an argument for robust climate adaptation planning in the face of uncertainty. *Environment Systems and Decisions*, *34*(4), 478–491. https://doi.org/10.1007/s10669-014-9528-z

Surminski, S., & Leck, H. (2017). From agenda-setting to implementation: The role of multisectoral partnerships in addressing urban climate risks. *Earth's Future*, *5*(10), 966–978. https://doi.org/10.1002/2016EF000497

Susskind, L. (2010). Responding to the risks posed by climate change: Cities have no choice but to adapt. *Town Planning Review*, *81*(3), 217–235. https://doi.org/10.3828/tpr.2010.5

Tangney, P. (2019). Does risk-based decision-making present an ‘epistemic trap’ for climate change policymaking? *Evidence & Policy: A Journal of Research, Debate and Practice*, (June 2019). https://doi.org/10.1332/174426419x15577476002113

Thompson, E., Frigg, R., & Helgeson, C. (2016). Expert judgment for climate change adaptation. *Philosophy of Science*, *83*(5), 1110–1121. https://doi.org/10.1086/687942

Thomsen, D. C., Smith, T. F., & Keys, N. (2012). Adaptation or manipulation? unpacking climate change response strategies. *Ecology and Society*, *17*(3). https://doi.org/10.5751/ES-04953-170320

Tol, R. S. J. (2005). Adaptation and mitigation: Trade-offs in substance and methods. *Environmental Science and Policy*, *8*(6), 572–578. https://doi.org/10.1016/j.envsci.2005.06.011

Tompkins, E. L., & Adger, W. N. (2004). Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society*, *9*(2). https://doi.org/10.5751/ES-00667-090210

Tompkins, E. L., Adger, W. N., Boyd, E., Nicholson-Cole, S., Weatherhead, K., & Arnell, N. (2010). Observed adaptation to climate change: UK evidence of transition to a well-adapting society. *Global Environmental Change*, *20*(4), 627–635. https://doi.org/10.1016/j.gloenvcha.2010.05.001

Tretter, E. M. (2009). The cultures of capitalism: Glasgow and the monopoly of culture. *Antipode*, *41*(1), 111–132. https://doi.org/10.1111/j.1467-8330.2008.00658.x

Trobia, A. (2011). Questionnaire. In *Encyclopedia of Survey Research Methods* (pp. 885–886).

Tsoukiàs, A. (2008). From decision theory to decision aiding methodology. *European Journal of Operational Research*, *187*(1), 138–161. https://doi.org/10.1016/j.ejor.2007.02.039

Turcotte, M. M., Corrin, M. S. C., & Johnson, M. T. J. (2012). Adaptive evolution in ecological communities. *PLoS Biology*, *10*(5). https://doi.org/10.1371/journal.pbio.1001332

Tyler, S., & Moench, M. (2012). A framework for urban climate resilience. *Climate and Development*, *4*(4), 311–326. https://doi.org/10.1080/17565529.2012.745389

Tyler, S., Nugraha, E., Nguyen, H. K., Nguyen, N. Van, Sari, A. D., Thinpanga, P., … Verma, S. S. (2016). Indicators of urban climate resilience: A contextual approach. *Environmental Science & Policy*, *66*, 420–426. https://doi.org/10.1016/j.envsci.2016.08.004

UKCIP. (2003a). Climate adaptation: Risk, uncertainty and decision-making. In *Policy*. https://doi.org/10.1016/j.molcel.2011.04.017

UKCIP. (2003b). Climate adaptation: Risk, uncertainty and decision-making. *Policy*, (May), 4 pp. https://doi.org/10.1016/j.molcel.2011.04.017

UKCIP. (2007). *Identifying adaptation options*. Retrieved from .

UKCIP. (2009). *A local climate impacts profile: how to do an LCLIP*. https://doi.org/978-1-906360-09-2

UKCIP. (2013). About the Wizard. Retrieved August 16, 2020, from https://www.ukcip.org.uk/wizard/about-the-wizard/

UKCIP. (2018). *Local Climate Impacts Profile: Spreadsheet notes*. Retrieved from https://www.ukcip.org.uk/wizard/current-climate-vulnerability/lclip/

Umwelt Bundesamt. (2015). Klimalotse - Supporting management of climate change risks and chances (decision support system). Retrieved October 17, 2019, from https://www.umweltbundesamt.de/en/topics/climate-energy/climate-change-adaptation/adaptation-tools/project-catalog/klimalotse-supporting-management-of-climate-change

Undorf, S., Allen, K., Hagg, J., Li, S., Lott, F. C., Metzger, M. J., … Tett, S. F. B. (2020). Learning from the 2018 heatwave in the context of climate change: are high-temperature extremes important for adaptation in Scotland? *Environmental Research Letters*, *15*(3). https://doi.org/10.1088/1748-9326/ab6999

Undorf, S.. (2019). Large increase in projected heatwave frequency for Scotland under new UK climate projections. Retrieved from ClimateXChange website: https://www.climatexchange.org.uk/blog/large-increase-in-projected-heatwave-frequency-for-scotland-under-new-uk-climate-projections/

United Nations. *Paris Agreement*. , (2015).

United Nations. (2018). World Urbanization Prospects. In *Demographic Research* (Vol. 12). Retrieved from https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf

Urban, F. (2018). Modernising glasgow-tower blocks, motorways and new towns 1940-2010. *Journal of Architecture*, *23*(2), 265–309. https://doi.org/10.1080/13602365.2018.1446182

Uusitalo, L. (2007). Advantages and challenges of Bayesian networks in environmental modelling. *Ecological Modelling*, *203*(3–4), 312–318. https://doi.org/10.1016/j.ecolmodel.2006.11.033

Vafaei, N., Ribeiro, R. A., & Camarinha-Matos, L. M. (2018). Data normalisation techniques in decision-making: Case study with TOPSIS method. *International Journal of Information and Decision Sciences*, *10*(1), 19–38. https://doi.org/10.1504/IJIDS.2018.090667

van de Ven, F. H. M., Snep, R. P. H., Koole, S., Brolsma, R., van der Brugge, R., Spijker, J., & Vergroesen, T. (2016). Adaptation Planning Support Toolbox: Measurable performance information based tools for co-creation of resilient, ecosystem-based urban plans with urban designers, decision-makers and stakeholders. *Environmental Science and Policy*, *66*, 427–436. https://doi.org/10.1016/j.envsci.2016.06.010

Van Der Gaag, L. C., & Helsper, E. M. (2004). Defining classes of influences for the acquisition of probability constraints for Bayesian networks. *Frontiers in Artificial Intelligence and Applications*, *110*(October), 1103–1104. https://doi.org/10.1007/978-3-540-30202-5

Van Der Sluijs, J. P., & Wardekker, J. A. (2015). Critical appraisal of assumptions in chains of model calculations used to project local climate impacts for adaptation decision support - The case of Baakse Beek. *Environmental Research Letters*, *10*(4). https://doi.org/10.1088/1748-9326/10/4/045005

van Dongeren, A., Ciavola, P., Viavattene, C., de Kleermaeker, S., Martinez, G., Ferreira, O., … McCall, R. (2014). RISC-KIT: Resilience-Increasing Strategies for Coasts - toolKIT. *Journal of Coastal Research*, (66), 366–371. https://doi.org/10.2112/si70-062.1

Van Ierland , E.C. , de Bruin, K. and Watkiss, P. (2013). *Multi-Criteria Analysis: Decision Support Methods for Adaptation, MEDIATION Project, Briefing Note 6*.

Van Ierland, E. C. ., De Bruin, K. ., & Watkiss, P. . (2013). *Decision Support Methods for Climate Change Adaptation: Multi Criteria Analysis. MEDIATION Project.*

van Vliet, M., van Buuren, A., & Eshuis, J. (2015). Action research for the governance of adaptation climate change - Conclusions and lessons learnt. In *Action research for Climate Change Adaptation. Developing and applying knowledge for governance* (pp. 182–196). New York: Routledge.

Varis O and Kuikka S. (1997). *BeNe-EIA: A Bayesian approach to expert judgment elicitation with case studies on climatic change impacts on surface wa- ters. Climatic Change 37: 539-563.* 539–563.

Vermeulen, S. J., Challinor, A. J., Thornton, P. K., Campbell, B. M., Eriyagama, N., Vervoort, J. M., … Smith, D. R. (2013). Addressing uncertainty in adaptation planning for agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(21), 8357–8362. https://doi.org/10.1073/pnas.1219441110

Vitabile, S., Farruggia, A., Pernice, G., & Gaglio, S. (2013). Assessing coastal sustainability: A Bayesian approach for modeling and estimating a global Index for measuring risk. *Journal of Telecommunications and Information Technology*, *2013*(4), 5–15.

Vogel, K. (2013). Applications of Bayesian Networks in Natural Hazard Assessments. *Natural Hazards and Earth System Science*, *1*(5), 5805–5845. https://doi.org/10.5194/nhessd-1-5805-2013

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling and Software*, *25*(11), 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007

Waajen, A. C. (2019). *The increased risk of water scarcity in Scotland due to climate change and the influence of land use on water scarcity: issues and solutions*. Retrieved from www.climatexchange.org.uk

Wagner, S. (2010). A Bayesian network approach to assess and predict software quality using activity-based quality models. *Information and Software Technology*, *52*(11), 1230–1241. https://doi.org/10.1016/j.infsof.2010.03.016

Waite, D., Maclennan, D., & O'Sullivan, T. (2013). Emerging city policies: Devolution, deals and disorder. *Local Economy*, *28*(7–8), 770–785. https://doi.org/10.1177/0269094213500122

Walsh, D.; McCartney, G.; Collins, C.; Taulbut, G. (2016). *History, politics and vulnerability: explaining excess mortality in Scotland and Glasgow*.

Watkiss, P;, Hunt, A., & Blyth, W. (2013). *Real Options Analysis: Decision Support Methods for Adaptation. MEDIATION Project.*

Watkiss, Paul. (2015). A review of the economics of adaptation and climate-resilient development. In *Centre for Climate Change Economics and Policy*. Retrieved from http://www.vfmadaptation.com/Working-Paper-205-Watkiss.pdf

Watkiss, Paul, & Hunt, A. (2013). *Method Overview: Decision Support Methods for Adaptation, Briefing Note 1. Summaryt of Methods and Case Study Examples from the MEDIATION Project*. 12. Retrieved from http://www.mediation-project.eu/platform/pbs/pdf/Briefing-Note-1-LR.pdf

Watts, M. (2017). Commentary: Cities spearhead climate action. *Nature Climate Change*, *7*(8), 537–538. https://doi.org/10.1038/nclimate3358

Webb, R., & Beh, J. (2013). *Leading adaptation practices and support strategies for Australia: An international and Australian review of products and tools*.

Weber, E. P., & Khademian, A. M. (2008). Wicked problems, knowledge challenges, and collaborative capacity builders in network settings. *Public Administration Review*, *68*(2), 334–349. https://doi.org/10.1111/j.1540-6210.2007.00866.x

Weber, P., & Jouffe, L. (2003). Reliability modelling with dynamic Bayesian networks. *IFAC Proceedings Volumes (IFAC-PapersOnline)*, *36*(5), 57–62. https://doi.org/10.1016/S1474-6670(17)36470-4

Webler, T. (2002). Unlocking the Puzzle. *Bulletin of Science, Technology & Society*, *22*(3), 179–189.

Wedekind, V. (1990). Obscuring Power: A critique of action research. *Knowledge, Method ...and the Public Good*, (January 1997), 331–352.

Wei, Q. (2018). Understanding of the naive Bayes classifier in spam filtering. *AIP Conference Proceedings*, *1967*(May). https://doi.org/10.1063/1.5038979

Wellman, M. (1986). Qualitative Probabilistic Networks for Planning Under Uncertainty. *Proceedings of the Second Conference on Uncertainty in Artificial Intelligence*, 311–318. Retrieved from https://arxiv.org/abs/1304.3115

Wellman, M. (1990). Fundamental concepts of qualitative probabilistic networks. *Artificial Intelligence*, *44*(3), 257–303. https://doi.org/10.1016/0004-3702(90)90026-V

Werners, S. (2013). *Adaptation Turning Points: Decision Support Methods for Adaptation, MEDIATION Project, Briefing Note 9*.

Westerhoff, L., Keskitalo, E. C. H., & Juhola, S. (2011). Capacities across scales: Local to national adaptation policy in four European countries. *Climate Policy*, *11*(4), 1071–1085. https://doi.org/10.1080/14693062.2011.579258

Whyte, B., Young, M., & Timpson, K. (2021). *Health in a changing city : Glasgow A* *study of changes in health , demographic , socioeconomic and environmental factors in Glasgow over the last 20 years*. (August).

Wilbanks, T., & Fernandez, S. (2014). *Climate Change and infrastruCture, urban systems, and Vulnerabilities*. https://doi.org/10.5822/978-1-61091-556-4

Wilbanks, T. J. (2007). Scale and sustainability. *Climate Policy*, *7*(4), 278–287. https://doi.org/10.1080/14693062.2007.9685656

Wilby, R., & Dessai, S. (2009). Robust adaptation to climate change. *Royal Meterological Society*, 180–185. https://doi.org/10.1002/wea.504

Wilby, R. L., & Vaughan, K. (2011). Hallmarks of organisations that are adapting to climate change. *Water and Environment Journal*, *25*(2), 271–281. https://doi.org/10.1111/j.1747-6593.2010.00220.x

Williams, S. J. (2012). Information Gaps and Science Needed to Support Sustainable Coasts. *Coastal Impacts, Adaptation, and Vulnerabilities*, 119–124. https://doi.org/10.5822/978-1-61091-460-4_6

Willows, R. I., & Connell, R. . (2003). *Climate adaptation: Risk, uncertainty and decision-making. UKCIP Technical Report*.

Wilson, C. (2014). Semi-Structured Interviews. *Interview Techniques for UX Practitioners*, 23–41. https://doi.org/10.1016/b978-0-12-410393-1.00002-8

Wise, R. M., Fazey, I., Stafford Smith, M., Park, S. E., Eakin, H. C., Archer Van Garderen, E. R. M., & Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, *28*, 325–336. https://doi.org/10.1016/j.gloenvcha.2013.12.002

Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2004). *At Risk: Natural Hazards, People's Vulnerability and Disasters*. Routledge.

Yawson, R. M. (2015). The "wicked problem construct" for organisational leadership and development. *International Journal of Business and Systems Research*, *9*(1), 67–85. https://doi.org/10.1504/IJBSR.2015.066812

Young, O. R., Berkhout, F., Gallopin, G. C., Janssen, M. A., Ostrom, E., & van der Leeuw, S. (2006). The globalization of socio-ecological systems: An agenda for scientific research. *Global Environmental Change*, *16*(3), 304–316. https://doi.org/10.1016/j.gloenvcha.2006.03.004

Yu, J., Castellani, K., Forysinski, K., Gustafson, P., Lu, J., Peterson, E., … Brauer, M.

(2021). Geospatial indicators of exposure, sensitivity, and adaptive capacity to assess neighbourhood variation in vulnerability to climate change-related health hazards. *Environmental Health: A Global Access Science Source*, *20*(1), 1–20. https://doi.org/10.1186/s12940-021-00708-z

Založnik, M., Bonsall, M. B., & Harper, S. (2021). The Qualitative Stage of Building Bayesian Belief Networks in a Focus Group Setting: Decision-Making under Uncertainty among Vietnamese Rice Farmers. *Sociological Methods and Research*, *50*(1), 75–102. https://doi.org/10.1177/0049124118769094

Zarei, E., Azadeh, A., Khakzad, N., Aliabadi, M. M., & Mohammadfam, I. (2017). Dynamic safety assessment of natural gas stations using Bayesian network. *Journal of Hazardous Materials*, *321*, 830–840. https://doi.org/10.1016/j.jhazmat.2016.09.074

# Appendix I Action Research Log

| Date | Event | Time (hours) | Type of Action Research Activity |
|---|---|---|---|
| 03/09/15 | Resilience Meeting GCC | 1.5 | Observer |
| 17/09/15 | Resilient Glasgow Game Workshop | 3.5 | Active participant |
| 30/09/15 | Resilient Glasgow Game | 3 | Active participant |
| 16/11/15 | Resilient Glasgow Working Group Institutions | 1 | I organised in terms of room booking and circulating agenda |
| 23/11/15 | Resilient Glasgow Working Group Economy | 1 | Observer |
| 27/11/15 | Resilient Glasgow Cross Cutting Working Group | 1 | Observer |
| 1/12/15 | Resilient Glasgow Steering Group | 2 | Observer |
| 04/12/19 | Meeting with CRO | 1 | Discussion |
| 09/12/15 | Resilient Glasgow Working Group call | 1 | Observer |
| 11/01/16 | Resilience Lens Workshop | 6.5 | Active participant |
| 12/01/16 | Resilience Lens Day 2 – Review and Confirmation of Initiatives | 3 | Active participant |
| 13/01/16 | Resilient Glasgow Steering Group | 2 | Observer |
| 24/02/16 | Resilient Scotland conference | 7 | Conference |
| 25/02/16 | Resilient Glasgow Steering Group | 2 | Observer |
| 08/04/16 | Meeting with GCC Resilient Glasgow Leads – Catch up / informal interview | 1 | Discussion |
| 27/04/16 | PI Sub Group Planning with GCC | 1 | Organiser |
| 03/05/16 | SMR Workshop | 6 | Active participant |
| 06/05/16 | Interview with Sniffer – Adaptation Scotland Manager | 1.5 | Interview |

| | | | |
|---|---|---|---|
| 15/05/16 | Interview with GCC Resilient Glasgow Leads | 1.5 | Interview |
| 16/05/16 | Interview with Melbourne CRO | 1 | Interview |
| 20 /05 – 25/05/16 | DACAS Conference | 1 | Conference |
| 28/05/16 | Interview with GCC Resilient Emergency Response Team Leader | 1 | Interview |
| 29/05/16 | Interview with ARUP | 1 | Interview |
| 12/06/16 | Interview with GCC Resilient Emergency Response Team Member | 1 | Interview |
| 19/06/16 | Interview with Scottish Fire and Rescue | 1 | Interview |
| 21/07/16 | Glasgow Resilience Strategy Public Engagement talk at Partick Library | 2 | Observer |
| 09/08/16 | Indicators Workshop Planning meeting | 1.5 | Active participant |
| 11/08/16 | Resilient Glasgow Indicators Workshop | 3 | Facilitator |
| 23/08/16 | Meeting with Climate Ready Clyde Lead | 1 | Discussion |
| 24/08 – 26/08/16 | URBACT Summer school in Rotterdam (I attended on behalf of GCC) | 16 | Training |
| 29/08/16 | Meeting with GCC climate adaptation lead | 1 | Discussion |
| 30/08/16 | Glasgow Climate Change Adaptation Task Group | 1.5 | Observer |
| 01/09/16 | Resilient Glasgow Strategy Release Event | 5 | Observer |
| 05/09/16 | URBACT Meeting with GCC | 1 | Discussion |
| 12/09/16 | PI Subgroup | 2 | Organiser |
| 21/09 - 23/09 | URBACT Knowledge Exchange Conference | 14 | Conference |
| 30/09/16 | Resilient Glasgow Steering Group | 2 | Observer |
| 31/10/16 | Meeting with GCC adaptation lead to discuss LCLIP | 1 | Discussion |
| 02/11/16 | Resilient Possilpark Scoping meeting | 1.5 | Facilitator |
| 04/11/16 | Meeting with Climate Ready Clyde Lead | 1 | Discussion |

| | | | |
|---|---|---|---|
| 16/11/16 | Indicators Meeting | 2 | Active participant |
| 25/11/16 | Resilient Glasgow Steering Group | 1.5 | Observer |
| 28/11 – 29/11/16 | CRC Adaptation Scotland Accelerator | 14 | Training |
| 05/12/16 | Meeting with GCC Resilient Glasgow lead | 1 | Discussion |
| 07/12/16 | GC Adaptation Task Group | 1 | Observer |
| 15/12/16 | Call with Climate Ready Clyde Lead | 1 | Discussion |
| 11/01/17 | Climate Adaptation Workshop Planning | 1.5 | Active participant |
| 17/01/17 | PI Subgroup Web Meeting | 2 | Organiser |
| 18/01/17 | GC Adaptation Work and LCLIP Meeting with SM | 1 | Discussion |
| 25/01/17 | Glasgow Climate Adaptation Workshop | 5 | Facilitator |
| 08/03/17 | Meeting with GCC Adaptation Lead | 1 | Discussion |
| 24/03/17 | City Building Glasgow Interview | 1 | Interview |
| 28/03/17 | City wide climate adaptation next steps and synergies with CRC discussion | 1 | Discussion |
| 03/04/17 | Interview with Transport Scotland | 1 | Interview |
| 04/04/17 | Interview with South Seeds | 1 | Interview |
| 07/04/17 | Interview with SP Energy Network | 1 | Interview |
| 10/04/17 | Interview with SNH | 1 | Interview |
| 10/04/17 | Interview with Resilient Emergency Response | 1 | Interview |
| 12/04/17 | Interview with GCU | 1 | Interview |
| 13/04/17 | Interview with University of Strathclyde | 1 | Interview |
| 21/04/17 | Interview with GCVGN | 1 | Interview |
| 24/04/17 | Climate Resilient Glasgow Taskforce meeting | 1 | Observer |
| 26/04/17 | Interview with Police Scotland | 2 | Interview |
| 27/04/17 | Interview with MGDSP | 2 | Interview |

| | | | |
|---|---|---|---|
| 28/04/17 | Interview with Carbon Management | 1 | Interview |
| 28/04/17 | Interview with Education Services | 1 | Interview |
| 11/05/17 | Interview with GCC Transport Planning | 1 | Interview |
| 15/05/17 | CRC Accelerator | 6 | Training |
| 5/06-09/09/17 | ECCA Conference – 2 presentations on research on GCC | 6 | Conference |
| 13/06/17 | Climate Adaptation Taskforce Meeting | 1 | Observer |
| 22/08/17 | Climate Resilient Glasgow – Infrastructure and Built Environment Workshop | 4 | Observation and BBN Qualitative network development |
| 23/08/17 | Climate Resilient Glasgow – Society & Economy | 3 | |
| 28/08/17 | Climate Resilient Glasgow – Natural Environment Workshop | 4 | |
| 12/10/17 | Meeting with Climate Ready Clyde lead | 1 | Discussion |
| 02/02/18 | BBN Expert elicitation – Expert #1 | 2 | Expert Elicitation |
| 01/12/18 | BBN elicitation – Expert #2 | 2.5 | Expert elicitation |
| 11/01/19 | BBN elicitation – Expert #3 | 1.5 | Expert elicitation |
| 10/05/19 | Interview with adaptation lead on BBN to appraise options | 2 | Expert validation |
| 14/06/19 | Interview with CRO | 1 | Interview |
| 02/09/19 | Glasgow Heat QPN Workshop – Part 1 | 6 | QPN Creation – expert elicitation |
| 27/11/19 | Interview with adaptation lead | 2 | Interview |
| 04/02/20 | Glasgow Heat QPN Workshop – Part 2 | 6 | QPN Creation – expert elicitation |
| 04/02/20 | Interview with adaptation lead | | Interview |
| Total Hours | | 204 hours | |

## Appendix II Resilience Strategy Interview Questions

- What year did the City Council actively start working on the concept of “resilience”? How was resilience and climate resilience interpreted by the organisation?
- Who took the initiative to apply to the 100 RC programme?
- What governance arrangements were made to apply to the 100 RC programme?
- Which groups/departments of the City Council were appointed/established to work on the application of the 100 RC?
- What city stakeholders were involved in the application?
- What resources were needed to prepare the application?
- What data was consulted and analysed to understand current resilience situation?
- Where there any data gaps identified?
- Which challenges were overcome to apply for the 100 RC programme?
- City Resilience Strategy
- When did the city resilience strategy start to be developed?
- Duration/ time required to develop the city resilience plan?
- How is the city resilience strategy presented to the public (city stakeholders)?
- Is the city resilience strategy aligned with regional, national, and international resilience management guidelines?
- What existing working groups collaborate with Glasgow City Council in the development and implementation of the resilience strategy?
- What city stakeholders participated or are actively participating in the development of the city resilience strategy?
- What is the relationship between Resilient Glasgow and different levels of governance also working on resilience?
- When will the city strategy plan be implemented?
- How will the different city stakeholders be involved in the implementation of the city resilience strategy?
- What resources are needed to implement the city resilience strategy?
- Which challenges need to be overcome to implement the city resilience strategy?
- Has a working group been established to monitor and evaluate the effectiveness of the city resilience strategy?
- Which stakeholders are involved/will be involved in the monitoring and evaluation working group?
- What will the impacts of monitoring and evaluating be on future funding to continue projects?
- How will monitoring and evaluating be used to shape future iterations of the resilience strategy?
- Are there platforms to enhance sharing of resilience lessons learned and best practices among city stakeholders?

## Appendix III LCLIP and Adaptation Strategy Interview Questions

1. What are the current climate risks recognised by your organisation? What do you think is the biggest climate risk to your organisation? Is climate change or extreme weather recorded in your risk register?
2. What are the main ways in which your organisation is disrupted during extreme weather events?
3. How have extreme weather events had an effect on your…
    - Customers or communities
    - Places and buildings
    - Public service delivery
    - Logistics
    - Business
    - Employees/ People
    - Budgets
    - Partners
    - Reputation

4. Are there any other factors, which combined with extreme weather and future climate, put a strain on your organisation and service provision? i.e. increasing population, aging population, changes to service demand etc.

5. Do you believe the consequences of climate change threaten your ability to maintain your reputation as an effective service provider?

6. How does climate change effect your organisation's long-term strategic goals?

7. Do you monitor/record extreme weather events and their impacts? If so, how is this done?

8. Did any of the following extreme weather events affect your service?

    - Excessive rainfall and flooding during August 2011
    - High winds of December 2011-January 2012
    - Storms of January 2016
    - July 2013 or June 2016 Heatwaves

9. How did this event effect your service?
    - Affects ability to carry out existing projects
    - Affects ability to contact service users
    - Affects quality of service / time available to deal with clients.

10. What financial cost has your organisation or department had to bear due to the cost of running extra equipment during extreme weather events?

11. What financial cost has your organisation or department had to bear due to overtime during extreme weather events?

12. To what extent did climate related events and service disruptions disproportionately affect vulnerable groups?

13. In what other ways have extreme weather events disrupted your operations?

14. Are any indirect or secondary impacts noticed or recorded?

15. What are the relationships between climate impacts across different sectors? Are there partnership agreements between your organisation and other urban service providers?
16. What services or organisations do you interact with when dealing with extreme weather events?
17. How is your communication with other agents in emergency Council, police and fire services during weather events?

18. Do you think your organisation has adequate frameworks in place to learn lessons from every extreme weather event?

19. Were any critical thresholds passed that had an impact on your operations? Or are there climate thresholds identified within your organization? For example, a wind speed above which operations have to stop for health and safety reasons; a temperature threshold above which staff performance or customer complaints increase significantly; a point at which quality of service fines maybe imposed. *Responses were recorded in table format (shown below) where possible.

| **Type of Weather Event** | **Specific Event** | **Identify any critical thresholds** | **Impacts** | **Consequences** | **Actions taken to address impact** | **Effectiveness of those actions** | **Source & Credibility of Information** |
|---|---|---|---|---|---|---|---|
| High summer temperature | 2012 Summer Temperatures in excess of 30C | Internal office temp exceeded 28 C | Offices overheated | Staff uncomfortable | Relax dress code, flexible working hours, fans | Effective but needed initial high spend to purchase fans and water | Past experience. Reliable. |

20. Is there a goal to be more prepared for adverse weather events and future climate impacts what does that entail?

21. What measures are currently in place to deal with adverse weather? How effective have these been previously?

22. What improvements have there been in service provision during periods of extreme weather in recent years?

23. Have any preparations/ adaptations been made since the event?
    - E.g. Research or training
    - Standards or policies
    - Changes to infrastructure
    - Changes to operations
    - What are the potential adaptation options and how would they work?

24. How are adaptation decisions or resilience plans currently made?

25. And what decision support tools or methods are utilised?

26. Is a risk management approach taken or a decision-making framework utilised?

27. What information is currently consulted when making climate resilience decisions?
28. Is there any further information or data needed to support adaptation decisions and actions?

29. What attributes would you want in a decision support system for climate resilience?

30. How are various adaptation options considered and compared? What criteria would adaptation options be evaluated against?

31. What are the factors which encourage or discourage the implementation of adaptation measures?

32. What constraints exist to your service fully adapting to the threat of climate change and extreme weather events? What are the barriers to taking measures for climate adaptation within your organisation? What features of your organization hindered your response? (E.g. could be financial, institutional, cultural or organizational)

33. Are there certain “windows of opportunity” recognised for taking action on climate change, i.e. in funding bids or new developments, or routine maintenance?

34. How do you monitor and evaluate the effectiveness of any adaptation activities?

## Appendix IV Questionnaire #1 Climate Resilient Glasgow - May 22nd, 2017, Workshop Questionnaire

Name and Department (optional):

1. How much impact (if any) do you expect climate change will have on Glasgow City Council?
   - Climate change will have a great deal of impact on our council
   - Climate change will have a fair amount of impact
   - Climate change will have some impact, but not much
   - Climate change will have no impact on our council
   - Not sure

2. To what extent has your expectation or perception that climate change will affect Glasgow City Council changed since participating in today's workshop?

   Decreased greatly Decreased slightly Stayed the same Increased slightly Increased greatly

3. For the following types of information, please identify to what extent it assists in understanding climate impacts and making the case for climate adaptation?

| | Not helpful | Somewhat helpful | Very helpful |
|---|---|---|---|
| Analysis of media reports of weather events and impacts | | | |
| Anecdotal comments on experiences of weather events | | | |
| Non-economic quantitative evidence of weather impacts (e.g. # of calls to emergency services) | | | |
| Economic costs of weather events and impacts | | | |

4. What do you see as the greatest benefits of improved knowledge of climate impacts? Please tick as many as apply.
   - Raising awareness within council
   - Engaging citizens with their own experiences / Community communication
   - Stimulating adaptation action
   - Risk management
   - Informing decision-making
   - General information
   - Identification of vulnerable regions, species and/or populations
   - Development of adaptation plans
   - Informing engineering design
   - As a communication tool
   - Incoproated into other municipal plans
   - Other – please explain

5. In relation to the 15 key consequences of climate change identified in the Scottish Government's Climate Change Adaptation Programme: Climate Ready Scotland, please indicate the likely level of impact on your council department's operations.

| | Unsure | No Impact | Minor Impact | Moderate impact | Major impact |
|---|---|---|---|---|---|
| Productivity of agriculture and forests | | | | | |
| Occurrence of pests and disease | | | | | |
| Quality of soils | | | | | |
| Health of Natural Environment | | | | | |
| Security of food supply | | | | | |
| Availability and quality of water | | | | | |
| Increased risk of flooding | | | | | |
| Change at coastline (sea level rise) | | | | | |
| Health of marine environment | | | | | |
| Resilience of businesses | | | | | |
| Health and wellbeing of people | | | | | |
| Cultural Heritage and Identity | | | | | |
| Security and efficiency of energy supply | | | | | |
| Performance of buildings | | | | | |
| Infrastructure – network connectivity and interdependencies | | | | | |

6. There is enough evidence and understanding of how weather events affect Glasgow to address climate impacts and effectively plan for adaptation.
   Strongly Disagree Disagree Unsure Agree Strongly Agree

7. What do you believe is your department's level of preparedness for responding to climate change impacts?
   Not prepared Fairly Prepared Very Prepared Unsure

8. Please rate the degree to which each of the following is a challenge when trying to address climate impacts or promote climate adaptation in your department.

| | No Challenge | Minor Challenge | Moderate Challenge | Major Challenge | N/A |
|---|---|---|---|---|---|
| Getting people to understand the nature of the problem | | | | | |
| Obtaining accurate scientific data | | | | | |
| Obtaining sufficient scientific data | | | | | |
| Making data relatable / creating an accessible narrative around it | | | | | |
| Securing funding for adaptation | | | | | |
| Getting information about how to plan for climate impacts | | | | | |
| Getting buy-in from other departments | | | | | |

## Appendix V Questionnaire #2 Climate Resilient Glasgow August 2017 Workshops

1. On a scale of 1-10 (1=no understanding at all, 10=very good understanding) how would you rate current understanding of the effects of climate change and their impacts on the natural environment in Glasgow?

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

2. In your view, what, if any, are the opportunities that may arise for the natural environment in Glasgow in connection with climate change?

3. Climate change affects the running of your organization…

Not at all A little Moderately Quite a lot Unsure

4. Can you quantify the aggregate losses from climate hazard events for your organization in financial terms?

Yes No

5. What is the motivation for your organization (or department) to participate in the Climate Resilient Glasgow Adaptation strategy workshops?

6. What are the main adaptation objectives for your organisation?

7. Did you propose an action and if so how was this action identified?

8. What do you believe are the main restrictions or barriers to adaptation in your own organization and/or within the wider Glasgow city context?

9. What scale do you see as most appropriate for climate adaptation planning?
   - ○ Community Planning Partnerships
   - ○ Local Authority
   - ○ City-Region
   - ○ National
   - ○ International
   - ○ All of the above

10. Is it clear to you the actors, and their roles and responsibilities, working on adaptation at the municipal, city-region and national scale?
    - ○ Yes
    - ○ No
    - ○ Partly
    - ○ Unsure

11. Do you believe the Scottish Climate Change Adaptation Programme adequately accounts for and enables multi-level governance? Y/N and if possible explain.

12. What, in your opinion, are the most important contributing factors to Glasgow being or becoming a ‘climate resilient city’?

13. Do you have any suggestions, comments or feedback on today’s workshop and the adaptation strategy process so far?

# Appendix VI Validation interview questions with Netherlands and Northern Ireland Stakeholders

PhD research has been undertaken (in Scotland) exploring (i) the influences on climate adaptation decision-making in city councils and (ii) how decision-making processes may be supported via participatory, qualitative, causal mapping workshops vs quantitative expert elicitation and modelling. A research interview with CAS is requested to learn more about adaptation decision-making in cities in the Netherlands to enable comparison with Scottish findings. The interview will be semi-structured. This document highlights the indicative questions to be asked.
Thank you in advance for taking the time to participate in this interview – your time is much appreciated!

**Section One – Discussion on the broad influences on adaptation (decision-making) in city councils / local authorities in the Netherlands**

1. Could you please describe the external context that influences adaptation within local authorities in the Netherlands (e.g., national policy, funding, citizen pressure etc.)?

2. What internal characteristics of local authorities affect adaptation (e.g., organisational structure, power dynamics, history, senior management, political landscape etc.)?

3. Is there a common approach to adaptation planning in Dutch cities (e.g., Adaptation Wizard, RESIN Framework etc.)?

4. What data and evidence is used to inform adaptation planning and decision-making?

5. How are adaptation options typically identified and prioritised?

    a. Is the option identification and appraisal process affected by:
        - Consultation / stakeholder engagement
        - Risk assessment
        - Organisational priorities or objectives
        - Available funding

6. Are decision support tools used to aid options identification, prioritisation and selection? If so what, tools/methods?

**Section Two -Testing out Protocol to aid selection of decision support methods**
Research identified a number of challenges in identifying and appraising adaptation options. As such two different decision support approaches were tested in practice. One was quantitative mathematical modelling, the other more qualitative and participatory. A protocol is being developed to guide practitioners and researchers in identifying when each approach may be most appropriate. This will be further explained and illustrated during the interview. The five themes considered in the

protocol are (i) awareness and understanding, (ii) resource, (iii) data availability, (iv.) stakeholder participation and (v.) expert elicitation – the following section highlights *draft* prompt questions – to discuss at the interview.

7. **Awareness and Understanding**
- *Is there awareness of climate impacts / adaptation in organisation?*
- *Do leaders dismiss issue or recognise as problem?*
- *Do the actors perceive a need to respond?*

*A 'yes' response to the prompt question implies 'sufficient' awareness and understanding to progress through the options identification and appraisal process. This is defined here as:*
- *Cross organisation support and understanding of adaptation*
- *Leadership and authority*
- *Governance and agency to take adaptation action*

8. **Resourcing**
- *Is there financial budget available for decision support?*
- *Is resource available for specialist software?*
- *Have sufficient time allocations of staff been made?*
- *Are there near term deadline and time pressures? Or is more / sufficient time available?*
- *How much options appraisal / facilitation skill is there among staff?*
- *Is there expertise to do options assessment internally?*

9. **Data Availability**
- *Is data and evidence (historic and present) currently available?*
- *Is data collection ongoing? Will information be regularly updated?*
- *Does the desired information exist? And is it accessible?*
- *Has there been a thorough canvas/consideration of all alternative options available?*
- *Do actors have control over the process of developing options?*
- *Do pre-existing policy agenda pre-determine the range of options being developed?*

10. **Stakeholders**

- *Would stakeholders be willing to participate in a workshop to inform options appraisal?*
- *Who would need to be involved in process?*
- *Is there a need to reach consensus? Or would one person have final say?*
- *In what ways are the stakeholders involved formally accountable?*

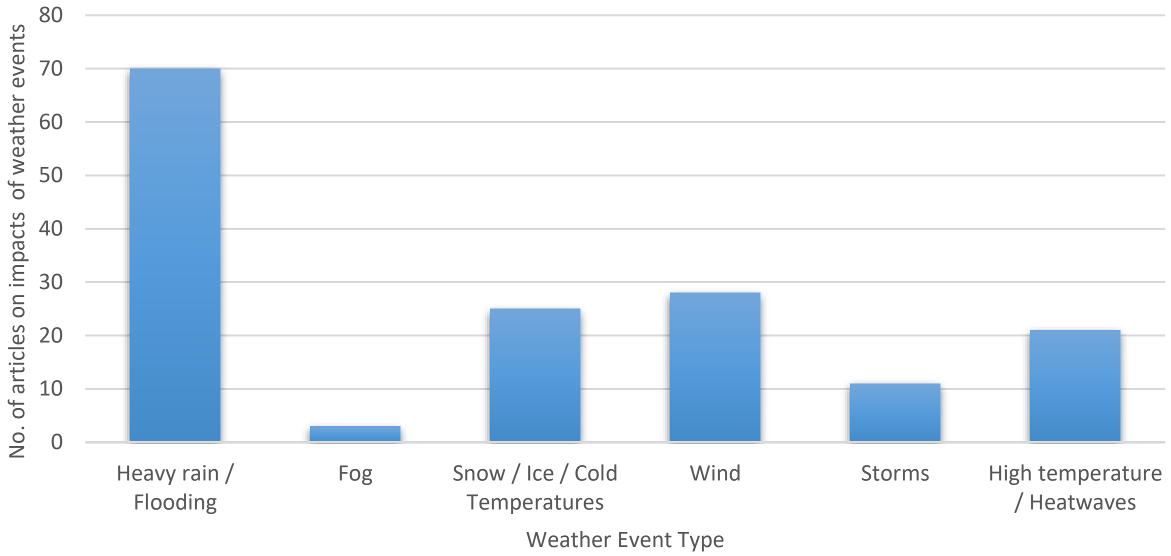
11. **Expert Elicitation**
- *Have you used expert elicitation? Do you think experts would be comfortable providing elicited probabilities?*
- *Do climate adaptation staff in Dutch local authorities often have technical scientific or mathematical backgrounds?*

- *How informed/ experienced are the experts?*
- *Are experts comfortable providing / eliciting probabilities, utilities and weights?*
- *Is training available?*
- *Are there staff available to assist who are trained on decision-making / competent?*

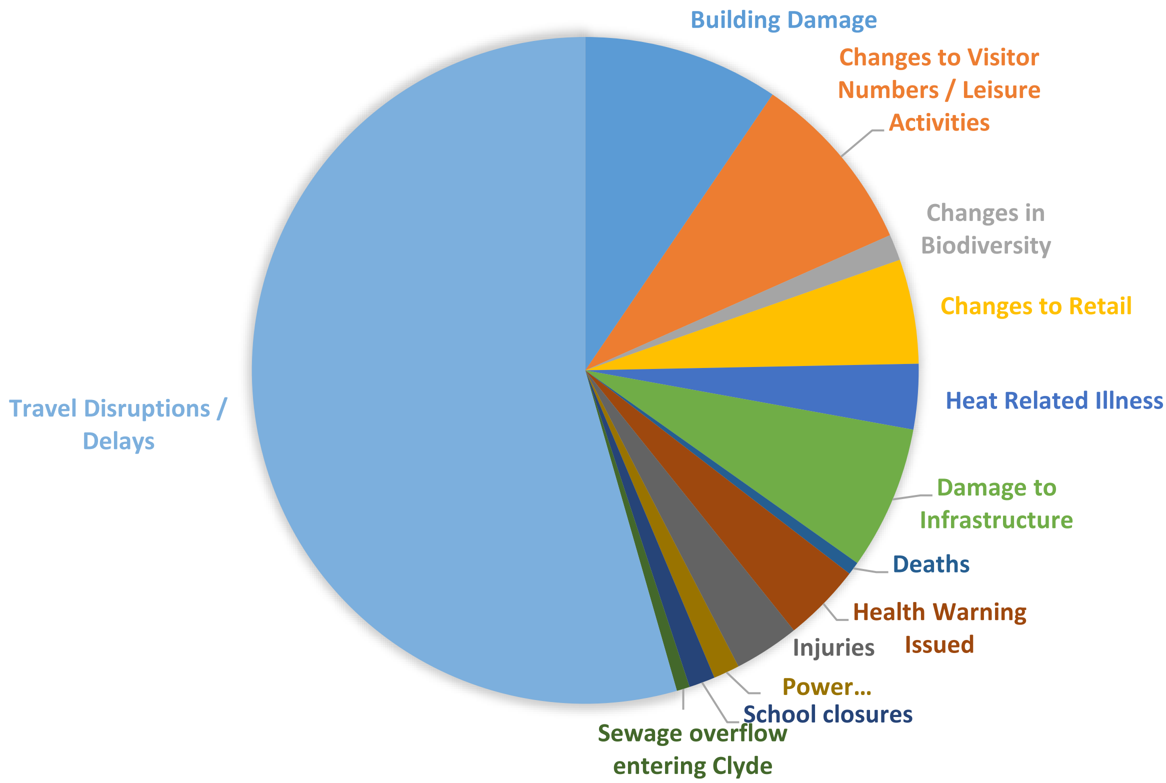
**12. Protocol**

- I will share my screen to show slides presenting the findings from Scotland and draft protocol to seek your feedback.
- Do you think methods to support practitioners in identifying and appraising options are needed?
- Would a protocol to help you understand which method is most appropriate in different settings be useful?

## Appendix VII LCLIP Results

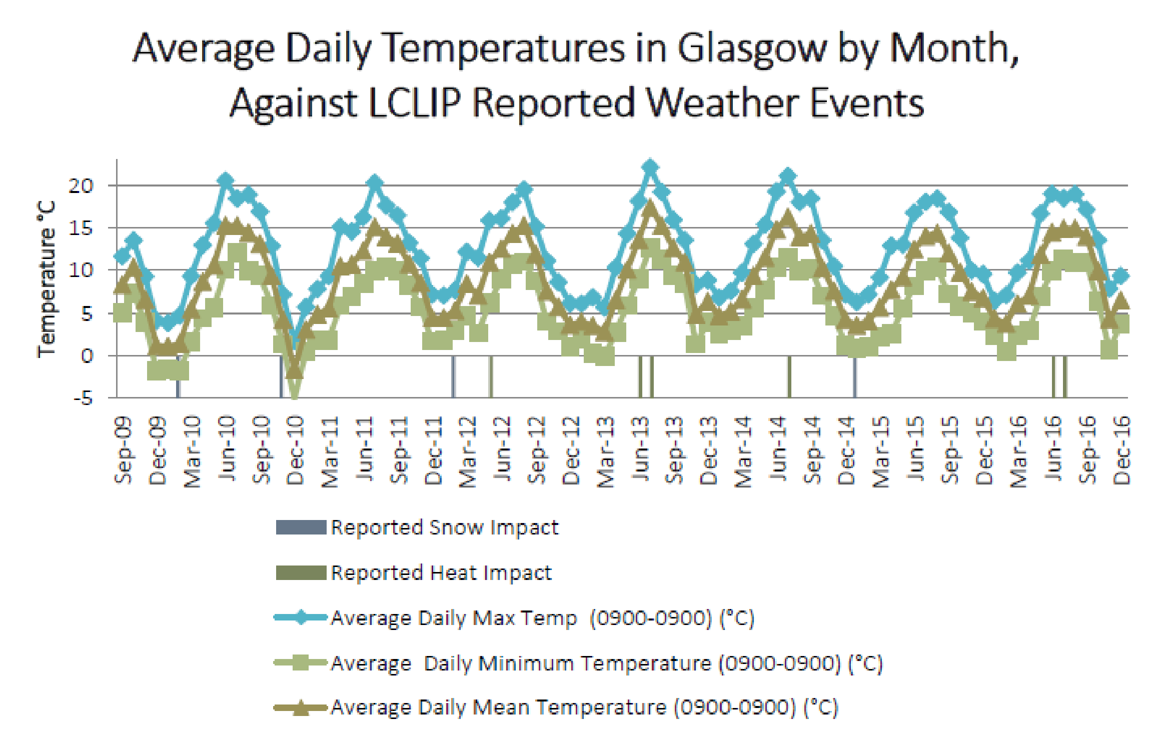



Media Reports of Weather Event Impacts Jan '07 - Jan '17




Impact types reported as % of all coverage

## Impact and consequences of high temperatures




| Impacts | Consequences |
|---|---|
| Change to Leisure | Parks and public spaces busy. Hillwalkers and climbers warned to take precaution when walking during heatwaves. |
| Changes to Retail | Increased food (BBQ) consumption, whilst high street sales decrease. |
| Heat related illness or discomfort / Health warning issued | Heatstroke and severe sunburn (especially serious for vulnerable groups including the very young, elderly and ill). Warnings over midge increases if warm and wet weather. Heatwaves causing air pollution levels to rise and create a health hazard – health warning issued for those with asthma. |
| Travel Disruption | Rail travel disruptions due to point failures as a result of thermal expansion of rail lines. |

# Case Study 1: Heatwave July 2013



Impacts on Society:

- *Increased use of green space and outdoor leisure activities*
- *BBQs associated with 27% increase (or 1,100 incidences) of food poisoning being reported to NHS Scotland this month*
- *Health warning issued – heightened number of individuals with heatstroke and severe sunburn seeking medical assistance*
- *Increased pressure on CORDIA –staff had to increase check-ins on elderly service users*


Impacts on Buildings and Infrastructure:

- *Increased energy consumption for cooling*
- *Universities reported renting fans temporarily*
- *Widespread rail disruption - point failures due to thermal expansion led to 1 in 10 journeys delayed on 10th July, 2013*
- *Glass buildings overheating – automatic fire brigade call outs and fines*

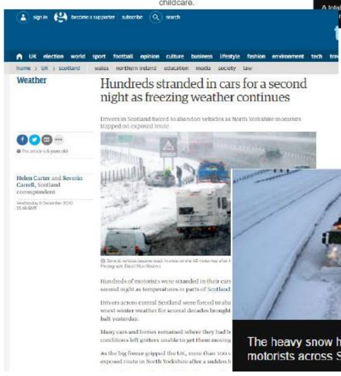
Impacts on Natural Environment:

- *Increased litter*

# Case Study 2: Winter 2010/11


Impacts on Society:

- *A total of 30 secondary schools, 147 primaries, 120 early years centres and 31 additional support for learning centres closed by GCC December 1st, 2010 – staff shortages due to childcare needs led to economic losses*
- *People suffering breaks and sprains by slipping on ice, road accidents – NHSGGC increase A&E admissions and emergency orthopedic trauma and prevalence of H1N1 increases*
- *Cold spell week prior to Christmas estimated to cost UK economy up to £1.2billion a day – shops footfall down and pubs badly hit*



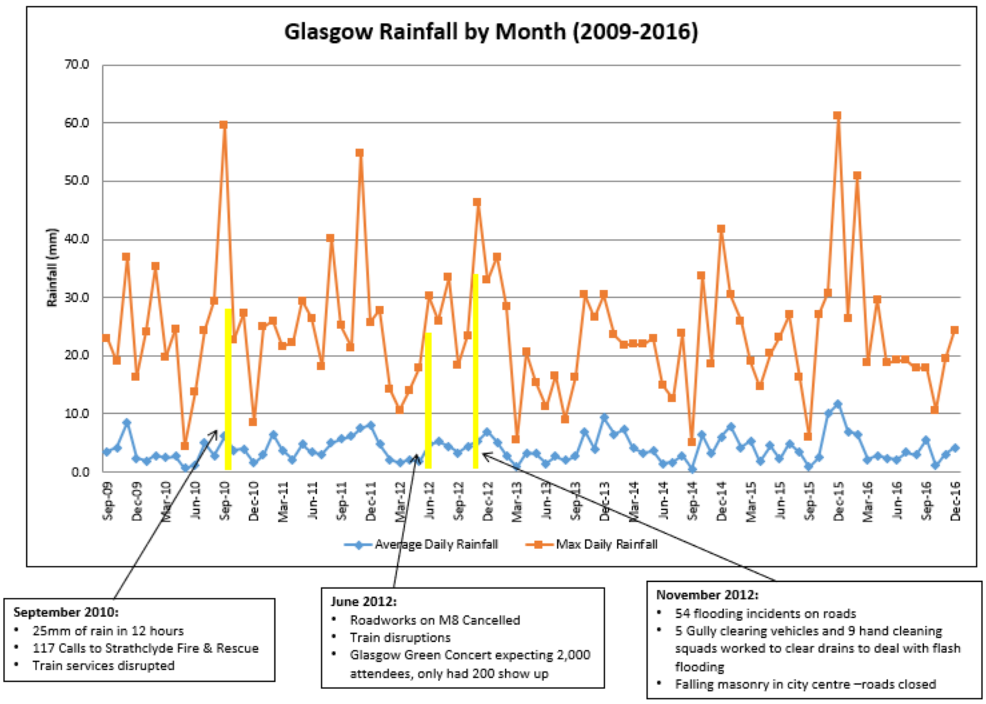


Impacts on Buildings and Infrastructure:

- *Increased pressure and spend to treat roads and pavements*
- *Widespread travel disruption*
- *Record demand for gas*
- *Increase in potholes*

## Impacts and consequences of increased precipitation

| Impact | Consequence |
|---|---|
| Travel Disruption | Train services disrupted (commonly Edinburgh – Glasgow route), Road accidents (resulting injuries/deaths), traffic at standstill / traffic jams. Subway and road closures. |
| Damage to Buildings | Homes flooded. Hillhead Primary School weather related power failure. |
| Damage to Infrastructure | Dalmarnock and Glasgow Central station damaged by flooding as well as Strathclyde Police's dog branch HQ located in Pollok country park. Partick subway station power lines disturbed. |
| Changes to Visitor Numbers and Leisure Activities | Cancellation or postponement of Christmas lights switch on. Glasgow Green Concert (June '12) expected 2000 attendees received 180 due to rain. SPL Football matches postponed or cancelled due to flooding on pitch. |
| Localised Surface Water Flooding | Leaves blocking drains – pooling of water on roads. |



# Case Study 3: Flooding July 5-7 2012

## Impacts on Society:

- *Strathclyde Fire and Rescue Service received 120 calls from householders and business owners concerned about flooding in 24 hours.*
- *Triathletes – norovirus*
- *Tourism – bookings cancelled*
- *Economic impacts – physical damage to flooded cars and properties*

## Impacts on built environment:

- *Both Central and Queen Street stations in Glasgow were forced to close (water damage to signals).*
- *Dalmarnock station flooded*

http://www.bbc.co.uk/news/uk-scotland-18716688

Flash flooding caused problems for drivers on Saracen Street in Glasgow

Services through Dalmarnock Station were seriously affected by flooding

City swamped as heavy rains cause flood chaos

Heavy flooding left cars stranded in Bilsland Drive

## Appendix VIII Training the Expert - Probability Training Exercise

This training section contains some questions to get you feeling conformable with questions related to probability.

1. Something that is unlikely to happen has a probability of between
   - and 0.5
   - 0.5 and 1.0
   - 1 and 2

2. Something that is likely to happen has a probability of between
   - and 0.5
   - 0.5 and 1.0
   - 1 and 2
3. What is the probability of rolling a 4 with a dice?
   - One sixth
   - One
   - Zero
4. What is the probability of getting 'heads' when you toss a coin?
   - 1
   - 0.5
   - 0.2
5. What is the probability of rolling an odd number with a dice?
   - One sixth
   - One third
   - One half

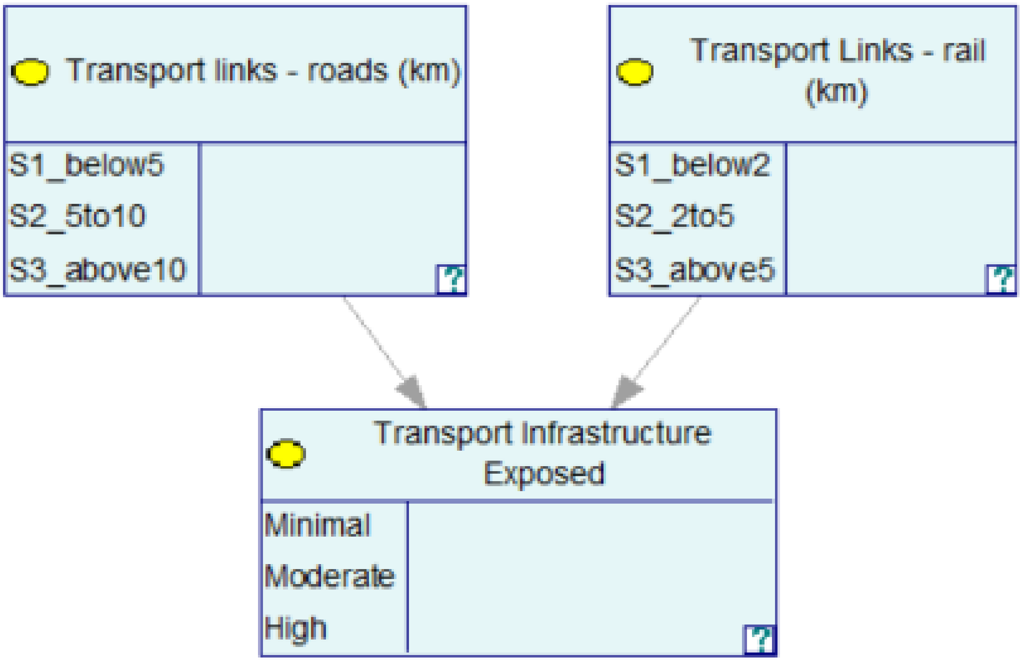
6. How many days do you expect it to rain in Glasgow in 2018? Consider the minimum and maximum number of days you think it might rain and record these numbers.

# Appendix IX Expert Elicitation of Conditional Probability Tables Example

In order to elicit values, the model will be broken down into small manageable chunks and we will focus on one criterion at a time. Therefore you (the expert) will only be provided with a segment of the BBN related to your expertise and experience and asked to define states of variables and conditional probabilities between dependent variables.

In this exercise you will be requested to provide your subjective opinion regarding the value of a small number of model parameters on which no direct information is available in the published research literature. Of interest to this research is both the value of your estimate and your uncertainty of what the true value may be. A very uncertain estimate is a legitimate result of the elicitation exercise and may be the most appropriate representation of knowledge on the topic area. As your expertise is in the field of <u>flood risk assessment</u> today we will focus on the segment of the model dealing with <u>exposure</u>. For the purpose of this study one will discretize each variable into states, minimal, moderate or high. There are two sub-sections dealing with the built environment and society exposure and the following questions will be structured to align with these categories.

<u>Transport Infrastructure Exposed</u>



How would you categorise states? Please provide feedback on below estimated states and probability of occurrences.

| | Transport Links -Roads (km) at Risk of Flooding | Transport Links – Rail (km) at risk of Flooding | 1st Expected state of “Transport Infrastructure Exposed” (Min, Mod, High) | Probability of the event | 2nd Expected State | Probability of the Event |
|---|---|---|---|---|---|---|
| 1 | S1_below5 - Low | S1_below2 - Low | | | | |
| 2 | S1_below5 - Low | S2_2to5 - Med | | | | |
| 3 | S1_below5 - Low | S3_above5 - High | | | | |
| 4 | S2_5to10 - Med | S1_below2 - Low | | | | |
| 5 | S2_5to10- Med | S2_2to5 - Med | | | | |
| 6 | S2_5to10 - Med | S3_above5 - High | | | | |
| 7 | S3_above10 - High | S1_below2 - Low | | | | |
| 8 | S3_above10 - High | S2_2to5 - Med | | | | |
| 9 | S3_above10 – High | S3_above5 – High | | | | |

# Appendix X Expert elicitation feedback questionnaire

- Did you understand the questions today?
- Do you understand the process?
- How challenging did you find the process of eliciting probabilities of states for nodes?
- How confident are you in your assignment of these probabilities? And if you're not confident what would help increase your confidence?
- How have you assigned probabilities to the effect of different adaptation options in the past?
- How challenging did you find assigning values to exposure given different states of society, built environment (and natural environment) exposure?
- Did this process make you think about the problem or concept of exposure differently?
- Do you think a tool that prompts decision makers to consider the consequences of their decision is useful?
- To what extent are decision-making tools required?
- How many states for each node are useful?
- Which nodes do you feel are most important for Glasgow City Council or a Scottish local authority?

# Appendix XI Description of BBN Nodes in Component 1: Exposure

## Component 1: Exposure

| Variable and units of measurement | States (based on SEPA data) | Justification for inclusion in BBN |
|---|---|---|
| **Built Environment** | | |
| Transport Links – roads (km) | Below 5 / 5 to 10 / Above 10 | These nodes were selected by stakeholders based on lived experience of disruptions to road and rail networks during previous flood events. It was seen that transport was important for delivery of goods and people in and out of the city. Climate change projections indicate that flooding of road infrastructure will increase in frequency and extent (ClimateXChange, 2016c). Pluvial flooding, specifically, poses greatest risk of road network flooding in Scotland with trunk roads being more exposed than road network as a whole (ClimateXChange, 2016c). Scotland has a medium risk exposure of rail to floods according to (Pregnolato & Dawson, 2018). |
| Transport links – rail (km) | Below 2km / 2 to 5 / Above 5 | |
| Utilities Exposed (units) | Less than 20 / High above 20 | Utilities include water, wastewater treatment and electricity substations located in areas at flood risk. This variable was identified by stakeholders as important but did not have first-hand experience or anecdotes relating to it.<br><br>Whilst climate change projections are expected to increase the threats of extreme weather (including flooding) on critical energy infrastructure, new guidelines on security of primary and grid substations are being implemented to enhance resilience (ClimateXChange, 2016b). |
| Residential property at risk of flooding (# of homes) | Less than 10 / 11 to 150 / 151 to 500 / 500 to 1000/ Above 1000 | Properties at risk of flooding (including both domestic and private) were identified by stakeholders as an important variable to represent in the BBN. This was because of stakeholder experience of being flooded directly. It was also suggested that properties exposed would influence people affected and related economic damages. |
| Non-residential property at risk of flooding (# of business properties) | Less than 10 / 11 to 150 / 151 to 500 / 501 to 1000/ Above 1000 | |
| **Society** | | |
| People (#) | Below 300 / 300 to 1500 / Above 1500 | People who could be affected by flood event was selected by stakeholders for inclusion. This was interpreted as wide ranging and relating to people being affected directly or indirectly as a result of the flood event. |

| | | |
|---|---|---|
| Community facilities in flood risk areas (# of units / facilities) | 0 / 1 to 5 / Above 5 | This was chosen by stakeholders as it was believed community facilities are important for community cohesion, service provision and potentially emergency response. |
| Designated cultural heritage sites (# of units / sites) | Below 5 / Above 5 | This node highlights the recognition that floods can affect elements of historical and cultural value as well, and the belief that this should be recognised in decision-making. |

# Appendix XII Description of BBN Nodes in Component 2: Adaptive Capacity

| Component 2: Adaptive Capacity | | | |
|---|---|---|---|
| **Section of BN** | **Node** | **States** | **Justification** |
| Ability to Prepare - relates to proactive or anticipatory adaptation | Population registered for Floodline alerts | Low (under 3,000) / High (over 3,000) | Scotland has a national flood alert system (Floodline) which stakeholders felt was useful in being able to prepare for floods. It has been found that those who engage with flood communications will have higher resilience levels (O'Sullivan et al., 2012). Contextual factors, such as location and social and cultural attributes, influence risk perception and thus responses to flood warnings (O'Sullivan et al., 2012). |
| | Level of knowledge of hazard | Low (no understanding or awareness of flood risk) / High (detailed understanding based on evidence and/or lived experience) | Level of knowledge of hazard was selected for inclusion by stakeholders based on the belief that resilience would be influenced if people had experienced a flood event directly or anecdotally (through friends, family or colleagues) which would enhance their level of knowledge of the hazard. Kuang & Liao (2020) proposed a Learning from Floods model to articulate the process of learning from flood experience and how it affects flood resilience. Their research suggests that experiencing a flood prompts individual and social learning. Knowledge of flooding can instigate management and action, if not impeded by barriers including information and resource availability, social capital and policy challenges, which were also alluded to in the BBN (Kuang & Liao, 2020).<br><br>However recent CXC IPSOS Mori research on flooding in Scotland shows the nuance in risk perception and action. Findings showed that those interviewed who had been flooded, even if aware of their property's flood risk as a result of lived experience or information, they did not see it as a significant or real risk. The report highlights this may be as a result of pluvial as opposed to fluvial flooding which is perceived as less of a threat (in Scotland) (Glencross et al., 2021). |
| | Properties with property level protection | Low (less than 10%) / High (above 10%) | The amount of properties with property level flood protection was selected by stakeholders as influencing ability to prepare. It was recognized that large-scale flood defences are not available |

| | | | |
|---|---|---|---|
| | | | throughout Glasgow and property-level flood protection may thus be needed and important. There is increasing recognition on the role of property level resilience as part of an integrated approach to flood risk management (Adedeji et al., 2018). Owusu et al. (2015) found that the majority of the public surveyed for their study (in Scotland) are willing to pay for property level flood protection. It was suggested that due to increasing impacts of flooding, coupled with tightened public budgets, the onus of flood protection would shift more towards property owners. |
| | Tenure Type | Owner occupied / social rented / private rented | Accommodation type influences flood resilience. Research indicates renters are typically not insured against flood damage to their contents. As Penning-Rowsell (2019) states, "The vulnerability to flooding of Scottish households with low incomes in rented accommodation is a most unsatisfactory situation, particularly as climate change appears to have greatest impact in increasing flood severity in such deprived and disadvantaged neighbourhoods." |
| Ability to React | Availability of emergency response items in household | Low (less than 20% of households) / High (over 20% of households) | The ability to react relates to a person or community's ability to respond to flood event and is affected by mobility and emergency infrastructure. |
| | Car ownership | None (no access to a car) / Available (access to one or more vehicles) | Stakeholders proposed that car ownership was influential on ability to prepare given that public transport may be adversely affected and not running in the event of a flood. Access to a car was seen as important to being able to evacuate and drive away / around areas where flooding had occurred. |
| | Public transport. Accessibility, frequency and diversity | Low (there are few routes and minimal redundancies amongst transport options) / High (there are ample transport offerings across trains and buses that are | This variable was selected by stakeholders in terms of resilience of transport system, i.e. if the trainline was affected was there an alternative bus route. This was seen as important in terms of leaving flooded areas and emergency response. |

| | | | |
|---|---|---|---|
| | | accessible and frequent) | |
| | Spatial distribution and capacity of emergency services | Low (under resourced services with long wait times) / High (well resourced services with broad geographic spread and low wait times) | Distribution of emergency services was selected by stakeholders for inclusion in the BBN. It was noted, however, that emergency services would be better placed to deal with significant evacuations or respond to specific buildings being flooded. It was seen as less important than individuals having resilience. |
| Ability to Recover | Insurance coverage of residents and business | Low (under 25%) / High (over 25%) | Insurance was identified by stakeholders as being key to being able to recover following a flood incident. The role of flood insurance compensating victims of flooding is a key tenet of flood risk management in the UK. Insurance rates in Scotland are low for low-income households and those in rented accommodation (Penning-Rowsell, 2019). |
| | Adults who would offer help to others in their neighbourhood in emergency | Low (under 20%) / High (over 20%) | Stakeholders felt strongly about including this node, stating that it signified social capital and local connections and trust. |
| | Citizens experiencing social isolation | Low (under 20%) / High (over 205) | Stakeholders selected this for inclusion stating that not experiencing social isolation would infer social integration and it was felt being involved in local community, clubs or societies would strengthen communication flows, access to resources and support. |
| | Voter turnout in parliamentary elections | Low (under 50%) / High (over 50%) | It was suggested that voter turnout is an indication of how active people in community are, and thus influences social capital and resilience. |
| | Social capital | Weak (there is little sense of community in relation to groups, networks and activities in area) / Strong (there is an established community with mixing of groups | Research suggests that ability to recover following a flood incident is related to social and economic safety nets, including neighbours and community groups (Glencross et al., 2021). Social networks and capital can assist with the flow of information and identification of available support for flood victims.<br><br>This recognition of social capital and networks may be especially pertinent to Glasgow. The city historically has experienced periods of forced change and rehousing through the creation of |

| | | |
|---|---|---|
| | and strong relationships amongst residents of area) | New Towns (as discussed in Chapter 4). In the 1900's selective redeployment of portions of Glasgow's population to create 'new towns' (as described in Chapter 4) had knock on consequences to the communities left including a capacity and leadership gap in the communities that stayed in Glasgow (Walsh et al., 2016). Social capital, or the relations among people that facilitate productive activity, is heavily influenced by participation, politicisation, community bonds, collective organisation (Coleman, 1988). These influences were all affected by de-industrialisation and led to the so called 'democratic deficit'.<br><br>Social capital influences climate adaptation processes (Adger, 2003) and the implications of previous events to alter social capital are needed to inform adaptation planning (as discussed in Chapter 6). The council has learnt from the experience of damaging social networks in relation to planning, but also consider the need for social capital in relation to flood resilience. Lower levels of adaptive capacity are also associated with locations experiencing high levels of poverty. |

# Appendix XIII Description of BBN Nodes in Component 3: Resilience of Public Sector Institutions

**Public Sector Institutions**

| Section of BN | Node | States | Justification |
|---|---|---|---|
| Organisational Culture & Assets | Resources for Adaptation | Sufficient (there is enough resources including data, human resources and funding & finance for flood resilience) / Insufficient (there is not enough resources available) | To make progress with adaptation, it will need to fit within an organisational culture and resources. Recognising that organisations operate within an existing governance and legislative structure which may influence their adaptation actions and response, is important (Bulkeley et al., 2011). Organisational adaptation planning will need to work closely with developments and alterations to wider governance and legislative structures. Secondly, it is vital that such structures are flexible and adaptive, as they have potential to influence the effectiveness or ability to take action (Brown et al., 2011). Leadership was highlighted as a factor influencing local capacity to adapt to climate change. This may arise from the role of individuals as leaders within a municipality, either policy entrepreneurs or political champions who push adaptation agenda (however the extent of these individuals influence is closely related to administrative structures, party politics and institutional capacity). For local authorities, leadership can influence municipal response and provide opportunities for municipalities to be leaders to their peer communities, for instance networks such as C40 cities or ICLEI (Bulkeley et al., 2011).<br><br>The BBN captured the importance of organisational culture and assets. For instance, it recognises the need to illustrate how adaptation complements or supports existing goals within the organisation and the need to ensure strong leadership roles occurring across the organisation, rather than few actors, as stressed by (Berkhout, 2012). |
| | Adaptation champions – colleagues engaged with CCA | Few (one or two individuals in the organisation knowledgeable and engaged on topic of adaptation) / significant (every team or department has a knowledgeable person progressing adaptation) | |
| | Governance arrangements | Weak (there has been no or little consideration of where flood resilience / adaptation decision-making should sit) / Strong (robust decision-making processes and governance arrangements in place and | |

| | | | |
|---|---|---|---|
| | | updated regularly) | |
| | Adaptation incorporated into org plans, procedures and policies | Low (adaptation mentioned in a few policies but mostly lip service) / High (adaptation effectively incorporated into range of policies) | |
| Understanding the Challenge of climate change and adaptation | Climate change risk assessment processes | Weak / Strong (organisation wide and project level risk assessments completed and updated regularly) | By understanding the challenge of climate change and adaptation, organisations can make informed decisions based on actual or expected change. Therefore, there is a need to gather evidence on climate risks and vulnerabilities, then integrate these into internal systems and procedures. |
| | Learning is integrated into internal processes | Weak (this is not yet occurring, there is lack of awareness and understanding across organisation) / Strong (robust processes are in place- widespread knowledge based on regular training and learning) | |
| Planning &Implementation for adaptation | Strategic vision & outcomes in places | Weak (ideas formulated but not yet refined) / Strong (vision co-created and widely endorsed) | Adaptation is a long-term challenge that requires strategic planning and implementation to achieve outcomes. Organisations therefore must have appraised options into an adaptation strategy and action plan, adopting an approach that maintains flexibility. Establishing a vision and communicating it were also seen as key steps in organisational adaptation. |
| | Adaptation strategy in place | Weak ( strategy not yet finished) / Strong (co-created, evidence-based strategy in place) | |
| | Actions implemented | Weak (actions are ad-hoc | |

| | | | |
|---|---|---|---|
| | and monitored | and/or responsive and not monitored) / Strong (actions are planned, proactive and monitored) | |
| Working Together | Well networked with external partners | Weak (early conversations but no formal relationships) /Strong (part of shared networks and strong relationships) | No organisation can adapt alone. Organisations must forge connections with key partners to share ideas and find opportunities to collaborate. It suggests that public bodies work together through pre-existing mechanisms and networks such as Community Planning Partnerships or through developing new partnerships in same geographic area or sector. Collaboration is an essential competence in any environmental action and more so in a context of adaptation: collaboration can reassure indecisive people and awaken a sense of self-efficacy, promote the dissemination of information, and increase a group's collective talents. However key parts of working together included understanding and respecting roles so that the limitations and boundaries of each role were well understood. The utility of forming strong alliances with others also helps share relevant expertise and removes barriers in the way of progress (OECD, 2003; Pruneau et al., 2013; R. L. Wilby & Vaughan, 2011). |
| | Governance & formal agreements for partnership in place | Weak (informal processes) / Strong (formal processes in place including MoU and shared ToR) | |
| | Implementing joint actions | Weak (ad-hoc joint action) / Strong (planned, pro active and well-resourced actions being implemented jointly) | |

# Appendix XIV Description of QPN Nodes

| **Node** (*denotes parent node with prior probability populated) | **Justification** |
|---|---|
| **Transport Exposed** | The LCLIP for Glasgow and conversations within the QPN workshops highlighted that key transport nodes such as Queen Street are adversely affected during high temperature days, with train delays and cancellations occurring. The prior probability was set at 33% likelihood that the true state of transport exposed would be occurring. |
| **Natural Environment Exposed** | As the first workshop explored changes to use and function of public realm, green space was highlighted as important and thus natural environment exposure included. This node was influenced by the three following variables. |
| Peatbogs drying out | This node was included given the peatbog present in Glasgow's Seven Lochs Nature Reserve. Evidence indicates that under climate change, peat bogs will experience drying due to warmer and drier summers. For instance, Ferretto et al., (2019) states "with the predicted increase of temperature and change in rainfall patterns due to climate change, the suitable area for peatlands might at best change location or at worst be reduced…climate projections forecast warmer and wetter winters and warmer and drier summers, which might not allow a waterlogged environment to be maintained throughout the year and might therefore compromise the entire process of peat formation." |
| Increased demand for water* | Published academic literature indicated that there may be an increased demand for water during heatwave events in Scotland, however this will be strongest for the East coast. As Waajen (2019) highlight "droughts will vastly increase in severity and frequency in the next decades due to climate change. This will have major impacts on Scotland's agriculture and citizens. We found that mainly East-Scotland is prone to water scarcity in the summer, and that the expected wetter winters will not be able to make up for the lower precipitation in the summer." Because of this the prior probability of this node being in the true state was set to 55%. |
| Increased non-native species* | Invasive non-native species are a significant threat to biodiversity (Bremner & Park, 2007). The prior probability of this node being in the true state was set to 55% given the indication of this trend, but lack of further additional Glasgow specific detail. |
| **Buildings Exposed** | One of the groups at the first workshop explored overheating to buildings, as such exposure of the built environment was included in the collated QPN. This node was influenced by the following five nodes. |
| High proportion of glass facades* | There was no publicly available data on this, however anecdotal evidence at the workshops and LCLIP findings indicated that buildings in Glasgow with glass facades were already experiencing overheating (for example GCU campus). As such the prior probability for this node being in true state was set at 52%. |
| High proportion of tall buildings* | No relevant data for this variable was identified. Prior probability was set at 51%. |
| Building retrofit and maintenance* | Due to anecdotal comments from stakeholders at workshops about lack of appropriate retrofit and maintenance recognising risks of overheating, the prior probability of true state was set at 45%. |
| Urban Heat Island (UHI) Occurring | There is evidence and published research showing that UHI is already occurring in Glasgow (Emmanuel & Krüger, 2012). Professor Emmanuel |

| | |
|---|---|
| | attended both workshops and contributed insight on Glasgow's experience of UHI. |
| High proportion of paced areas and impervious surfaces* | Glasgow has some of the highest proportions of sealed land in Scotland (ClimateXChange, 2016a). As such, likelihood of this node being in true state set to 60%. |
| **Sensitivity of Population** | This node was seen as particularly important, by stakeholders, for inclusion in network given how different population groups are affected by heatwaves differently. This node was influenced by following three variables. |
| High proportion of population living in areas of high SIMD* | Recent data (2020) shows that Glasgow has 43% of population living in SIMD – much higher than Scottish average. According to SG (2021) "based on SIMD 2020, Glasgow City has 331 zones (out of a total of 746) allocated to the most deprived 20% of locations in Scotland. Each SIMD 2020 area contains an average population of 800 people. Thus, in terms of its population, it means that 43% of Glasgow's citizens (268,200 people out of 621,000) are living in areas classified amongst the most deprived in Scotland". |
| High proportion of employees at heightened risk – outdoor workers and non-flexible work environments* | There was a lack of data on this. The workshop to develop the QPN was hosted pre covid and at that time it was felt that workplaces were not flexible hence why it was set to 55%, however this likely will have changed since COVID 19 and work from home policies for some sectors. |
| High proportion of population with long term health conditions (heart and breathing problems) * | In Glasgow, 24% of adults of working age report having a disability and mental wellbeing is consistently lower than other Scottish cities (Whyte et al., 2021).As such likelihood of this node being in true state was set to 60%. |
| **Adaptive Capacity** | This node related to what individuals and institutions could do to prepare and respond to heatwave events and was influenced by the following eight nodes. |
| High proportion of population have access to cooling or shade | Air conditioning and/or shading could help citizens cool down during an extreme heat event. |
| Public awareness of heat risk and response | This was felt important for citizens to be able to understand the risk of heatwaves and act accordingly. |
| Accessible information, knowledge, and data on heat risks available* | This node related to facts and evidence of the potential consequences of heatwaves on Glasgow. Due to stakeholder feedback, this was seen as low so a likelihood of 40% was assigned. |
| Planning policy integrates climate resilience* | Given that planning policy does not currently recognise high temperatures as a risk, the node was set to 40% likely. |
| Sufficient resource availability | As was discussed in Chapter 6, resources for climate resilience are extremely limited and this influences ability to adapt. |
| Mature adaptation capabilities amongst staff/ | Having the confidence, competence and capabilities to be able to adapt at an institutional level was regarded by stakeholders as relevant to achieving objective of resilience. |

| | |
|---|---|
| departments at council + public bodies | |
| Committed political leadership on climate change | As was found in Chapter 6, leadership commitments both at manager level and elected officials affected how climate change risks were perceived and resourced, so this was included within the network. |
| Local level decision-making and budgetary power * | It was recognised by stakeholders that in order for Glasgow to be resilient to heatwaves, it would be key that the city could make relevant decisions at the local level (such as planning mandates) and that it why this node was included. |

## Appendix XV QPN Workshop 1 Questionnaire

Name and Department or Organisation (optional):

1. To what extent has your expectation or perception that heatwaves will affect changed since participating in today's workshop?

Decreased greatly Decreased slightly Stayed the same Increased slightly Increased greatly

2. How did you find the structure of today's workshop (i.e. using the IPCC climate risk framework of exposure, sensitivity and adaptive capacity) to identify impacts and adaptation actions?

3. What do you see as the greatest benefits of improved knowledge of climate impacts? Please tick as many as apply.
    - o Raising awareness
    - o Engaging citizens with their own experiences / Community communication
    - o Identifying adaptation options
    - o Stimulating adaptation action
    - o Risk management
    - o Informing decision-making
    - o General information and data gathering
    - o Identification of vulnerable regions, species and/or populations
    - o Development of adaptation plans
    - o Informing engineering design
    - o As a communication tool
    - o Incorporated into other municipal plans – helping mainstream
    - o Other – please explain

4. What do you believe is your department or organisation’s level of preparedness or resilience to impacts of heatwaves?

Not prepared Fairly Prepared Very Prepared Unsure

5. What barriers, restrictors or challenges to address heatwave impacts or take adaptation action exist in your department or organisation?

6. What motivators, catalysts or drivers enable or support your department or organisation to address climate impacts and take adaptation action?

## Appendix XVI QPN Workshop 2 Feedback Questionnaire

Glasgow Heatwave Resilience Workshop Participant Questionnaire - Glasgow City Council, Wednesday February 5th, 2020

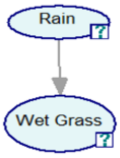
Introduction and Aim of Study: Often, in complex systems, it is hard to appreciate connections and how a change in any one element impacts upon the system as a whole. Furthermore, the specific local context (both physical and socio-economic) influences the effectiveness of interventions and must be understood and represented within climate adaptation decision-making in order to understand what contributes to resilient outcomes. As such research is being carried out on how to create an interactive Climate Resilient Model for Glasgow using a Qualitative Probabilistic Network (QPN) methodology to visualise the components of climate resilience and assess proposed adaptation actions. The aim of the model and related research is to enable one to explore causal relationships between factors which contribute to or minimise the impact of heatwaves and floods. This aims to assist with producing a prioritised list of adaptation actions to be included in the city's draft adaptation strategy.

Thank you for taking time to participate in this workshop, which has been organised to help inform research on climate resilience. This document contains a training exercise and post workshop questionnaire to be completed by each participant.

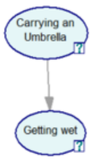
**Training Exercise**

Influence - A qualitative influence between two variables expresses how the values of one variable influence the probabilities of the values of the other. For example, a positive qualitative influence of a variable A, expresses that observing higher values for A makes higher values for B more likely.

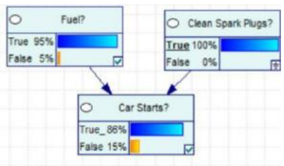
An influence may be positive (+), negative (-), zero (0) or ambiguous (?). Before we discuss influences in relation to heat resilience in our workshop, let's explore some examples.
What is the influence between rain and the likelihood of wet grass?



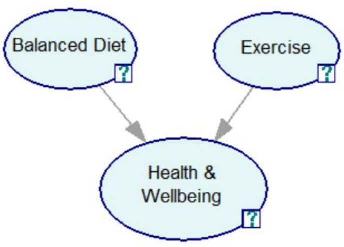

What is the influence between carrying an umbrella and the likelihood of getting wet?




What is the influence between having fuel and clean spark plugs and the likelihood that a car will start? Please annotate the influence of both variables.




Sometimes influences can relate to one another in a positive or negative manner, called synergies. When two influences are more positive when experienced in combination than individually, they have a positive synergy. When they have a worse outcome when taken together than individually, they have a negative synergy. What would the influences and synergies be between balanced diet, exercise and health and well-being?



**Reflection Questions**

An important element of this workshop is to seek feedback on how the process of developing the BN and how useful the produced output was for the purposes of appraising adaptation actions. Please provide your response to the following questions.

Did you understand the questions asked of you today?

How did you find assessing influences between nodes/ variables?

| Very Difficult | | | | | | Very Easy |
|---|---|---|---|---|---|---|
| 1 | | | | | | 7 |
| ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Comments:

How did you find assessing the strength of influences?

| Very Difficult | | | | | | Very Easy |
|---|---|---|---|---|---|---|
| 1 | | | | | | 7 |
| ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Comments:

How did you find assessing synergies or the interactions among influences?

| Very Difficult | | | | | | Very Easy |
|---|---|---|---|---|---|---|
| 1 | | | | | | 7 |
| ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Comments:

How did you find considering uncertainties?

Very Difficult Very Easy

1 ○ ○ ○ ○ ○ ○ ○ 7

Comments:

How did you find appraising adaptation actions?

Very Difficult Very Easy

1 ○ ○ ○ ○ ○ ○ ○ 7

Comments:

Do you think the network had too many or too few variables? Please explain.

Did this process make you think about/ understand/ interpret heatwave resilience differently?

Please indicate if the below criteria were achieved, by providing a numerical response on a 1-5 scale with 1 being strongly disagree to 5 being strongly agree and provide a comment below as to why you feel this.

| Criteria | Score | Comments |
|---|---|---|
| Ability to identify factors which contribute to or enhance climate resilience (in relation to heatwaves) and illustrates connections between them | | |
| Illustrating potential of proposed adaptation actions | | |
| Identifying which options would be most beneficial | | |
| Evaluating co-benefits of adaptation actions | | |
| Identifying and communicating uncertainties | | |
| Knowledge exchange & Consensus Building<br>To what extent did the process of creating and using the BN help share information amongst stakeholders and did process help build consensus on the topic? | | |
| Relevance to climate adaptation<br>Do you feel that this process/method is suited to understanding climate resilience in order to identify and appraise adaptation actions? | | |

# Appendix XVII BBN Options Appraisal and Feedback Questions

Questions posed to adaptation lead and main decision maker 10/05/19

**Adaptation Options Appraisal**

- What actions are proposed in the draft adaptation strategy to address pluvial flooding?
- For each option
    - How will this affect exposure? What nodes will it influence, and will this be positive or negative?
    - How will it affect adaptive capacity? What nodes will it influence, and will this be positive or negative?
    - How will it affect maturity of capabilities of your organisation? What nodes will it influence, and will this be positive or negative?
    - How will it affect sensitivity of the population? What nodes will it influence, and will this be positive or negative?
    - How is this option affected by other actions?
    - Would the affects of this intervention be different in different locals ,e.g. city centre vs area of high social index of multiple deprivation? Where in particular would it work best and why?

**Adaptation Options Implementation Scenarios**

- Which options do you see occurring together?
- What are the effects if they happen at the same time?
- Do you believe the impact of each option would be strengthened or hindered if done in conjunction with other options?
- What are the characteristics of locations that influence the success of adaptation interventions?

**Feedback on BBN approach**

- What do you like and dislike about the approach?
- Does it help you think about the problem and adaptation options in a different way?
- Would you use this approach in practice?
- Do you trust the results of the BBN?

## Appendix XVIII Protocol Support Prompt Questions and Responses

| Description / Justification | Prompt Questions | Responses |
|---|---|---|
| Awareness and understanding of climate adaptation<br>Methods to support decision-making can be incredibly useful; they can also take substantial time, energy and resource. Therefore, it is important to consider if a decision support process is endorsed and outputs likely to be used before embarking on using one. Chapter 6 demonstrated that leadership, organisational buy-in and awareness influenced adaptation progress in GCC. Whilst decision support methods do provide mechanisms to enable learning and raise awareness, they should only be used where some base knowledge and support exist.<br><br>Applied research of adaptation on the ground has shown how context influences decision-making (Siders and Pierce 2021). Internal factors within an organisation also affect a decision maker's selection of decision-making support. This could include previous experience, aims, resource, or goals. Where the organisation positions climate adaptation, and their commitment to it, will influence decision-making. As such, the level of awareness and understanding of the problem is the first consideration within the protocol.<br><br>Similarly, the threshold of concern of climate adaptation is a common barrier to adaptation in organisations (S. C. Moser & Ekstrom, 2010a). This is explored via actor's perception of climate impacts and the need to adapt. | Questions to consider at this stage in the protocol include:<br>Is there awareness of climate impacts / adaptation in organisation?<br>Do leaders dismiss issue as problem?<br>Do the actors perceive a need to respond? | A 'yes' response to the prompt question implies 'sufficient' awareness and understanding to progress through the options identification and appraisal process. This is defined here as:<br>Cross organisation support and understanding of adaptation<br>Leadership and authority<br>Appropriate funding<br>Governance and agency to take adaptation action<br><br>If the response is positive to the above questions, the user continues to the proceeding question within the protocol. If the response, is negative it is suggested that further awareness raising, and capacity building activities be undertaken and/or an alternative decision support method used. Further awareness raising and/or capacity building may articulate this urgency and encourage future participation in adaptation related decision-making and action. |
| **Resource Availability**<br>Structured decision-making approaches often need time and financial resource input and therefore it can be suggested these should only be used where the outcome is better than what you would achieve with less resource intensive heuristic or approach (Siders and Pierce 2021). Resource availability is thus one of the strongest influences on | Questions to consider in relation to financial resources:<br>Is there financial budget available for decision support?<br>Is resource available for specialist software? | There are three potential responses to the above questions within the protocol. If sufficient resources are identified, the next question explores data availability and is on the side of BBNs. Whereas a partial resource availability leads the use to next |

| | | |
|---|---|---|
| where decision support will be used, and if so what type of support. Resource constraint, particularly as a consequence of the Covid-19 pandemic, may affect (Scottish) city councils for the near future. In this protocol, three aspects of resource are identified including (i) finance, (ii) time and (iii) staff. These are based on the findings from research on GCC and have been validated in the literature.<br>Time may be a limited resource and thus should be considered when selecting a decision support method. There are often short timescales for decision-making in policy making which may necessitate methods which can be deployed quickly. Timing of actions can also be influenced by external pressures such as international or national legislation changes or citizen activism, as demonstrated in this study of GCC. As was discussed in Chapter 6, lack of time available to make the decision can lead to hypervigilant decision-making. As such time as a resource is considered within the protocol.<br><br>The staff time available as well as skill sets of staff will affect if decision support methods are viable. It is therefore important to consider the technical background and skill set of the decision-maker as a deciding factor on which decision support to choose. | to take adaptation action<br><br>Questions to consider in relation to time:<br>Have sufficient time allocations of staff been made?<br>Are there near term deadline and time pressures? Or is more / sufficient time available?<br><br>Questions to consider for competence and confidence of decision-maker:<br>How much options appraisal / facilitation skill is there among staff?<br>Is there expertise to do options assessment internally? | consider the availability and willingness of stakeholders to take part in participatory workshops, leading to QPN. Lastly, a response of no there are not sufficient resources instructs the user to undertake further awareness raising and capacity building in order to increase resourcing for adaptation. |
| **Data Availability**<br><br>A third element to consider when identify whether using BBN or QPN is appropriate, is the content (or data) available to inform options appraisal. There is a need for data and evidence on the climate risk (or problem) and how these change over time. Flexibility and the ability to update information and evidence is important in climate adaptation, so that decisions can be modified in response to developments and as information improves. This values the acquisition of additional information and adheres to the tenant of adaptive environmental management proposed by Holling (1978).<br><br>In addition to climate risk data, information on potential adaptation options is also needed. This research shows that thorough options identification is not always undertaken to inform decision-making. | Questions to consider for climate risk data:<br>Is data and evidence (historic and present) currently available?<br>Is data collection ongoing? Will information be regularly updated?<br>Does the desired information exist? And is it accessible?<br><br>Questions to consider for data on options:<br>Has there been a thorough canvas/consideration of all alternative options available? | If response to the above questions is yes then it is suggested that a BBN may be appropriate in this setting, whereas a response to no leads to stakeholder participation |

| | | |
|---|---|---|
| Instead, options which are pre-existing, have existing or secured funding or hold popularity with current managers or elected officials are selected. This is at odds with the proposed decision framework that suggests an organisation assesses all risks and identifies potential options to respond to such risks. Decision support tools should consider if all available decision options are available and/or desired. | Do actors have control over the process of developing options?<br>Do pre-existing policy agenda pre-determine the range of options being developed? | |
| **Stakeholder Participation**<br><br>Climate adaptation decision-making is challenging as it requires the involvement of multiple stakeholders from governments, academia, industry and civil society. Different stakeholders may have differing problem frames and/or goals (Siders and Pierce 2021). The GCC QPN study demonstrated the challenge in ensuring participation (for example the difficulties in getting participants to develop a BBN structure). Research also showed however the benefits in collaborative stakeholder engagement. The QPN process was more fruitful and useful through fostering relevant discussion and knowledge exchange between stakeholders. As such, this protocol asks users to reflect on if and how they require stakeholders to be engaged, as this will influence which method is most appropriate. The complexity of climate change necessitates tools which enable stakeholders to visualise the wide range of possible impacts (Goudine, Newell, and Bone 2020). The desired number of stakeholders to be engaged and the amount to which they can be involved in the decision-making process will influence method selection. | The following questions help explore this topic further:<br>Who will be involved in process?<br>Is there a need to reach consensus?<br>In what ways are the stakeholders involved formally accountable? | If the response to the above questions is yes – then a following question on format of expert elicitation is asked. If the response is negative, then the user is encouraged to explore alternative methods. |
| **Expert elicitation**<br><br>A problem in operationalising decision support may be that outputs or models are too complex psychologically if requiring elicitation of probabilities, utilities and weights. Assessment may require mathematical evaluation of utilities or values, or qualitative indications of which option has the most co-benefits. Similarly, evaluation may need specified probability distributions or simpler estimations of | **Expert elicitation**<br>As such, it is suggested the following questions be posed to aid selection:<br>How informed/ experienced are the experts? | The response to these questions may indicate if the 'experts' are more comfortable providing qualitative or quantitative information and suggest a QPN or BBN respectively. |

| | | |
|---|---|---|
| expected values or a small number of quantiles (Katsikopoulos et al., 2018). The analytical goal and evaluation approach will influence what decision support process is most relevant.<br>Different methodological choices will be more appropriate in different context and levels of knowledge. | Are experts comfortable providing / eliciting probabilities, utilities and weights?<br>Is training available?<br>Are there staff available to assist who are trained on decision-making / competent? | |

.

## Appendix XIX Protocol Validation Interview Responses

The protocol questions were posed to stakeholders from Northern Irish and Dutch climate adaptation intermediary organisations who provide support to local authorities in their nations. This section summarises the responses of both representatives to protocol prompts.

The interviewee from Northern Ireland highlighted that there was good awareness and understanding of climate change at the city level. Whilst it was commented there was plenty of ‘goodwill’, the lack of national legislation on climate (adaptation) however limits the support and motivation to undertake adaptation action by local authorities. In terms of resourcing, the response to the protocol questions was partially. This indicates some but insufficient resourcing available. This includes limited staff capacity for adaptation, and it is seen as part of one person’s job rather than included in departments across the organisation. This led to consideration of data availability with the response to the prompt questions being no, illustrating the evidence and ongoing data collection was not available. The interviewee stressed a lack of local level data, stating, “I think what that is missing in large part, is the socio-economic data and information on vulnerability is missing over here and certainly not easily accessible.” It was also commented that staff did not have the right skills sets to utilise data effectively, even if it was available.

The final section of the protocol assessment with Northern Irish representative provided a positive response to the stakeholder queries. Stakeholders are regularly engaged on adaptation. Previous experiences found that conversation and creating a space to bring people together to discuss the vulnerability and what options are needed, was found to be useful and support decision-making. However, it was felt that experts would only be able and comfortable to provide qualitative information within an expert elicitation session. It was felt that qualitative insight would be appropriate for their current decision support needs. The respondent stated, “I think what I would say is that for the most part, what I've uncovered about this is that most of the information is qualitative. Most of the decision-making falls to qualitative pieces bar the big capital projects. Almost everything else that I've found is qualitative work, and it's based on local expertise and experience.” Based on the interviewee responses, the protocol suggests a QPN would be well suited to the Northern Irish setting.

The protocol assessment with the Dutch representative revealed a different situation. In terms of awareness, yes there was understanding and awareness. However, it was noted that there was heightened awareness due to previous extreme weather events, rather than forward looking anticipation. Within the respondent Dutch cities, funding for adaptation was available (£300,000 euro annually), however the practitioner stated that they didn't have time, resource or capacity to spend it. In addition, it was indicated that appropriate data was not available. It was commented that there was a mismatch in data collection and use at the regional and local scales and that the data the local authority was using was out of date, and no plans or resources had been committed to update it.

Working through the second half of the protocol highlighted that city (climate adaptation) decision-making typically does not engage stakeholders across the city council or local community. It was commented that the local authorities role pertained more to informing rather than engaging stakeholders on adaptation. Similarly, expert elicitation was not found to be common practice in the culture of the Dutch local authorities. It was commented that water managers typically have more technical backgrounds and may be able to contribute but that the expertise and technical skill set of adaptation practitioners may depend on where adaptation is located in the municipality. Based on the interviewee responses, the protocol indicates a QPN approach may be appropriate however it depends on stakeholder engagement and further capacity building and awareness raising may instead be needed.

The application of the protocol advised on the use of QPNs for both practitioners. It should be noted, however, that QPN as a method may be a good precursor to a more detailed or quantitative decision support method. Complex systems, such as urban climate adaptation, are settings where confident numerical modelling is extremely challenging. Qualitative approaches which aid system understanding, can however, be a useful complement to numerical approaches (Dambacher, Shenton, & Hayes, 2007). QPNs provide an abstract version of probability theory. Whilst QPNs ignore the specific values of individual probabilities, it is argued by (Parsons, 2004) and found within this research that such abstraction is still suitable for planning, explaining and prediction activities.