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Development and Assessment of Adaptive Urban Flood Risk Infrastructure under Conditions of Deep Uncertainty

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Submitted in part fulfilment of the requirements for the degree of
Doctor of Philosophy in Civil and Environmental Engineering, September 2018

Declaration

I confirm that the work in this thesis is my own and I give appropriate references and citations whenever I refer to, describe or quote from the work of others, whether published or unpublished.

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September 2018

Abstract

Globally, the risk associated with urban pluvial flooding is growing due to the confluence of climate change and urbanisation. The inherently complex nature of these processes makes it unclear what the impacts will be— including when and where they will happen, or to what degree. It is therefore said that adaptation to these risks occurs under conditions of deep uncertainty. Deep Uncertainty implies that methods which were historically effective at planning are no longer appropriate. Regardless new infrastructure must be built and existing infrastructure adapted.

This thesis explores Decision Making under Deep Uncertainty and its implications for the sustainable long-term planning of drainage infrastructure. To address this issue, the effects of potential changes were explored through use of an Adaptation Tipping Points methodology. This methodology was highly modified to extend its applicability far beyond previous work. This method was applied to a case study which was modelled within Infoworks ICM, the drainage system was then stress tested against changes to the 30-year return period design storm. The effectiveness of 53 potential strategies to alleviate flooding by the potential changes were evaluated.

Adaptation Pathways were generated, providing decision makers information regarding incremental adaptations for changes in the depth and intensity of the design storm. It is shown that the most effective Adaptation Pathway can vary significantly depending on which changes to the design storm take place. This is due to the non-linear interaction of multiple drainage processes and the importance of path dependence.

This thesis developed a novel methodology to calculate the costs and benefits of a set of Adaptation Pathways. This method builds upon real options to provide a cost-benefit analysis which encompassed both flood benefits and ecosystem services. Furthermore, the effect of uncertainty on financial performance was assessed. It is shown that the financial performance of pathways is highly influenced by the order in which solutions are implemented. However, very rarely does the uncertainty surrounding a project's financial viability obfuscate whether it will be a success or not.

The final result was a set of fully costed Adaptation Pathways that decision makers could use to identify the best adaptation strategy.

Acknowledgements

The last four years have been a transformative process, and like all such processes the experience was not easy, smooth, and at times it was completely unpleasant. However, as is always true with these endeavours, the passage to the other side makes one stronger and reveals much about one's self.

I would not have been able to climb this metaphorical mountain without the support of many people.

I would like to thank my parents for their constant support over the last four years and helping me remember why I began the PhD. I'd also like to thank my brother for always providing levity when the light at the end of the tunnel seemed to move ever-further away.

I would like to thank my office mates of the last four years for their daily support, conversation, and willingness to accept my distractions; thank you Malcom, Simon, Chi San, Peter, Barbara, Zed, Claudia, and Tim.

Thank you to my supervisors Ana and Kaveh. Your guidance and willingness to support my ideas even when thy were undeveloped, non-standard, and a little crazy will always be appreciated.

Other people I would like to thank include Jimmy O'Keefe, Laura Bellamy, Jean Paul Vella, Ramandeep Singh, Sarah Willis, Mohamad El Hatab, Craig Buchannan, Clement Fevrier, Fiona Walport, Chris Cheeseman, and Tina Mikellides.

I would especially like to thank Fionnuala for all her help over the last five years- it is truly appreciated.

Thank you to the dozens of friends I have made outside of the Department over the years; especially Phoebe for being my flatmate of two years.

Come gather round people

Wherever you roam

And admit that the waters

Around you have grown

And accept it that soon

You'll be drenched to the bone

If your time to you is worth saving

Then you better start swimmin' or you'll sink like a stone

For the times they are a-changin'

-Bob Dylan

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Chapter 1

Introduction

1.1 Research Motivation

The risk of pluvial flooding poses unique challenges. Pluvial flood risk exists in all areas of the globe, unlike other risks which are concentrated around fault-lines, coasts, or rivers. Protecting against pluvial events which cause flooding is both difficult and expensive. Compared to other forms of flooding, such as coastal or fluvial flooding, the design return period of drainage infrastructure is very low. This is due to the profound difficulty of managing surface runoff, especially within dense impervious urban areas where people expect to live their day-to-day lives uninterrupted by extreme weather.

Cities are a tremendous asset to the planet-the clustering and economic growth that takes place within cities has resulted in huge economic growth, lifting millions out of poverty, and has helped further the development of knowledge by leaps and bounds. It is an unfortunate reality that it is precisely this density of people and assets that has made cities the most exposed and vulnerable areas of the globe to pluvial flooding. Widespread pluvial flooding in cities can cause millions of pounds of damage and large losses of human life. The huge expanses of impervious land in urban areas removes the ability of the soil to infiltrate run-off. This results in vast quantities of surface water that must be drained or managed.

Historically the management of surface water has been achieved through the use of drainage systems. Initially, drainage systems took the form of combined sewers. More modern drainage systems have attempted to separate storm water flows from foul water in order to reduce combined sewer overflows and allowing for the direct discharge of storm water into watercourses. These drainage systems were built to serve a vastly different hydrological environment from the one that currently exists within cities and must be adapted in order to deliver a reasonable level of pluvial flood protection.

As noted earlier, impervious land surfaces exacerbate pluvial flood risk by reducing the earth's natural infiltration ability. Around the globe, urban areas are growing at an unprecedented pace resulting in existing areas becoming denser and more impervious. Additionally, previously rural areas around the peripheries of cities are being settled, leading to a growth in impermeable areas. Simultaneously, climate change is increasing the probability of extreme weather events occurring. These extreme weather events include the severe precipitation events that lead to pluvial flooding.

Both of these factors; land use change and climate change, are exacerbating the risk of urban pluvial flooding. There is a need to develop an approach to adapt to this risk while also anticipating further growth in these risk aggravators. However, planning infrastructure systems under conditions of change is extremely difficult.

1.2 Research Aims and Objectives

It is evident that urban areas must be adapted to the growing risk of pluvial flooding. However, there are large uncertainties surrounding how land-use and the climate may change in the future. These uncertainties present serious challenges with regards to how to design drainage adaptations. These large uncertainties and their interactions lead to a state known as *deep uncertainty*. Problems of deep uncertainty should not be addressed using "traditional" modes of planning. Instead, appropriate Decision Making Under Deep Uncertainty (DMDU) methodologies should be applied. However, DMDU techniques have not been widely applied to the problem of urban drainage adaptation. Several questions arise when considering the intersection of these fields.

- What are the key drivers of change to be considered for an urban drainage deep uncertainty problem?
- What is an appropriate model for such an analysis, how should fidelity and speed be balanced?
- Which DMDU methods can be used for urban drainage design?
- How should policy makers choose between different solutions given by a DMDU analysis for urban drainage?

This thesis aims to discern whether DMDU methods are appropriate for use on urban drainage problems, and if so, to apply an appropriate DMDU methodology to a case study. The overall goal of these aims is to provide decision-making support for urban water managers attempting to develop adaptation strategies. To achieve this several research objectives were laid out:

- Identify the main drivers of change for pluvial flood risk and their associated uncertainties. Discern, based on these drivers whether the planning of urban drainage adaptations is exposed to "deep uncertainty".
- Analyse existing Decision Making under Deep Uncertainty methodologies and develop a new approach suited to addressing the problem of planning under deep uncertainty for urban pluvial flooding.
- Develop an appropriate flood simulation model to conduct a DMDU analysis for urban drainage systems.
- Generate a set of Adaptation Pathways using the developed DMDU framework and the flood simulation model
- Develop a method to financially assess the Adaptation Pathways generated for an urban drainage system.

1.3 Thesis Outline

To address the aforementioned research aims the following thesis structure was adopted.

In Chapter 2 the literature on growing pluvial flood risk, deep uncertainty, and Decision Making under Deep Uncertainty is investigated. It is asserted that planning urban drainage adaptations is undertaken under conditions of deep uncertainty and an appropriate DMDU methodology is identified.

In Chapter 3, the concept of antifragility is introduced within the concept of infrastructure planning; primarily with regards to urban water infrastructure.

In Chapter 4, the hydrological modelling framework utilised to identify Adaptation Tipping Points and simulate the flood characteristics of a case study was outlined.

In Chapter 5, the application of the Adaptation Tipping Points (ATP) methodology is described. This chapter also investigates what is the most appropriate urban rainfall run-off model for use within a DMDU analysis. This chapter culminates in a set of Adaptation Pathways for a case study in London.

In Chapter 6, the costs and benefits of the Adaptation Pathways generated were evaluated. This includes the capital expenditure, operational expenditure, flood risk reduction benefits, and the value of the ecosystem services provided by the potential adaptations.

In Chapter 7, the financial analysis presented in the previous chapter is built upon. The uncertainty surrounding projections is explored resulting in a more robust assessment of financial performance under change.

In Chapter 8, the conclusions of the work are presented and practical recommendations are laid out on how to adapt urban drainage systems under conditions of deep uncertainty.

1.4 Publications

The following papers and conference presentations were written or delivered over the course of this PhD and were based upon information presented within this thesis.

Conferences:

- The Development and Assessment of Adaptation Pathways for Urban Pluvial Flooding. *American Geophysical Union Annual General Meeting.* New Orleans, USA. December 2017.
- The Evaluation of Adaptation Pathways for an Urban Drainage System under Conditions of Deep Uncertainty. *Fifth Workshop on Decision Making under Deep Uncertainty.* Oxford, UK. November 2017.
- The Evaluation of Adaptation Pathways for an Urban Drainage System under Conditions of Deep Uncertainty. *Thirteenth International Conference on Urban Drainage.* Prague, Czech Republic. September 2017.
- The Efficacy of Blue-Green Infrastructure for Pluvial Flood Prevention under Conditions of Deep Uncertainty. *European Geophysical Union Annual General Meeting.* Vienna, Austria. March 2017.
- Adaptation Tipping Points Applied to a Catchment in the Greater London Area. *Fourth Workshop on Decision Making under Deep Uncertainty.* Washington D.C., USA. November, 2016.
- Systematic Planning of Adaptation Options for Pluvial Flood Resilience. *European Geophysical Union Annual General Meeting.* Vienna, Austria. March 2016
- A Theoretical Framework for Developing Resilience to Urban Pluvial Flooding. *Third Workshop on Decision Making Under Deep Uncertainty* November 2015.

Journal Articles:

- Babovic, F., & Mijic, A., Under Review. The Economic Evaluation of Adaptation Pathways for an Urban Drainage System. *Water*.

- Babovic, F., & Mijic, A., Under Review. Development of Adaptation Pathways for Long Term Planning of Urban Drainage Systems. *Journal of Flood Risk Management*.

- Babovic, F., Mijic, A. & Madani, K., 2018. Decision Making Under Deep Uncertainty for Adapting Urban Drainage Systems to Change *Urban Water Journal*, 15(6), pp.552-560. Available at: https://doi.org/10.1080/1573062X.2018.1529803.

- Babovic, F., Babovic, V. & Mijic, A., 2017. Antifragility and the development of urban water infrastructure. *International Journal of Water Resources Development*, 627(October), pp.1–11. Available at: http://doi.org/10.1080/07900627.2017.1369866.

The research questions and aims, are addressed in the journal articles and chapters of this thesis. They are connected following the relationships in Table 1.1

Table 1.1: Links between articles, objectives and questions

Question	Objective	Chapter	Journal Article
What are the key drivers of change to be considered for an urban drainage deep uncertainty problem?	• Identify the main drivers of change for pluvial flood risk and their associated uncertainties. • Discern, based on these drivers whether the planning of urban drainage adaptations is exposed to "deep uncertainty"	Chapter 2	Decision Making Under Deep Uncertainty for Adapting Urban Drainage Systems to Change
What is an appropriate model for such an analysis, how should fidelity and speed be balanced?	Analyse existing Decision Making under Deep Uncertainty methodologies and develop a new approach suited to addressing the problem of planning under deep uncertainty for urban pluvial flooding	Chapter 2 and 4	Development of Adaptation Pathways for Long Term Planning of Urban Drainage Systems.
Which DMDU methods can be used for urban drainage design?	Develop an appropriate flood simulation model to conduct a DMDU analysis for urban drainage systems	Chapter 2 and 4	Development of Adaptation Pathways for Long Term Planning of Urban Drainage Systems.
How should policy makers choose between different solutions	Generate a set of Adaptation Pathways using the developed DMDU framework and the flood simulation model	Chapter 5 and 6	The Economic Evaluation of Adaptation Pathways for an Urban Drainage System
given by a DMDU analysis for urban drainage?	Develop a method to financially assess the Adaptation Pathways generated for an urban drainage system	Chapter 5 and 6	The Economic Evaluation of Adaptation Pathways for an Urban Drainage System

Chapter 2

Identification of Research Gaps Through a Literature Review

2.1 Introduction

The world is undergoing a rate of change more rapid than ever witnessed before (Friedman, 2008). The global population is growing with increasingly significant proportions of this growth occurring within urban agglomerations (Geltner and de Neufville, 2012). Simultaneously, climate change continues to augment the uncertainty surrounding the future state of the world's hydrological and ecological systems. Both of these factors increase the pluvial flood risk that urban areas experience.

A significant subset of these hazards are related to water, encompassing issues such as water supply, flood protection, and coastal defence (Jha et al., 2012). Due to the dynamic nature of urban systems, their economic importance, and the multiple stresses acting upon them, there is a need to anticipate and develop long-term strategies for these challenges. The current planning paradigm of "predict and optimise" is insufficient for an increasingly uncertain future as it fails to account for errors in predictions (McInerney et al., 2012). Irrespective of these uncertainties, new infrastructure systems must be built, and existing ones adapted in such a way that they remain reliable in the future despite the potential changes in land use and climate that may occur.

This chapter explores the applicability of new methodologies for planning under deep uncertainty to deliver protection against urban pluvial flooding. Firstly, the drivers of change and their related uncertainties are discussed. Then an overview of decision-making under deep uncertainty (DMDU) methodologies is presented and recommendations are made on the selection of the most suitable DMDU approach for the problem of urban pluvial flooding. This chapter is based upon a journal article published in the Urban Water Journal (Babovic et al., 2018).

2.2 Changing Urban Flood Risk

The two main strands of the global change related to the urban flood risk that are being observed are 1) climate change and 2) changes in human settlement patterns.

2.2.1 Socio-Demographic Change

In recent decades there has been a movement of wealth from the Western world to the rest of the globe, particularly Asia (Friedman, 2008). The increased size and wealth of the world's population has resulted in the development of a new middle class with increased demands for water, food, transport, and other commodities. As a part of this transition certain populations are urbanising rapidly, thus concentrating assets and increasing the potential impact of climate hazards.

Urbanisation is defined as "the process of transition from a rural to a more urban society" (UNFPA, 2008, pp.6). The UNPD (2014, pp.1) states that few factors will influence the globe's development to the same extent as "the size, structure and spatial distribution of the world's population". In 2007, for the first time, half of the world's population resided in urban areas; this represents a rise from 746 million people in 1950 to 3.9 billion people in 2014. By 2050, it is estimated that 61% of the world's total population will be urbanised (United Nations Department of Economic and Social Affairs Population Division, 2014) . The United Nations

Department of Economic and Social Affairs Population Division (2014) provides an in-depth investigation into changing global demographic shifts. The migration of people from rural areas to cities stretches the capacity of existing infrastructure systems. In low income countries migrants generally arrive on the fringes of cities and form ad-hoc settlements with little or no-centralised control (UNPD, 2014). In the context of urban flooding these settlements are unlikely to have appropriate flood defence infrastructure and adhere to policy measures meant to reduce exposure to flood risk.

Projections of future population size and urbanisation should be treated cautiously as they are estimated by extrapolating the past behaviour of populations and are sensitive to various uncertainties (UNPD, 2014). Furthurmore, these historic behaviours may not be indicative of future growth dynamics. Population growth predictions are sensitive to differences in fertility rates which are in turn affected by a number of highly unpredictable factors such as access to birth control, women's education, and opportunities for women to work (UNPD, 2014). These uncertainties have resulted in a history of imprecise projection of population growth; Satterthwaite (2007) noted that the world is notably less urbanised than what was predicted with respect to the proportion of the population urbanised, the size of urban areas, and the total urban population.

2.2.2 Climate Change

Climate change can affect the statistical distribution of weather parameters by altering the mean, variance, or skewness of their distributions (IPCC, 2012). These changes in the frequency, intensity, and spatial extent of weather events can result in extreme events becoming increasingly probable (IPCC, 2012). To address climate change, actions must be taken immediately to reduce the quantity of greenhouse gases being released into the atmosphere despite the continued growth of the global middle class. The problem of climate change is compounded by thermal inertia, which states that excess heat will be stored within the atmosphere even if levels of greenhouse gases were to fall rapidly (Jenkins, 2010). Due to this, climate change adaptation is necessary as the effects of climate change will be observed at some level even with aggressive mitigation measures.

Climate change has the potential to significantly affect pluvial flood risk. The IPCC's Fifth Assessment Report's Working Group II concluded that it was likely that there had been increases in the number of heavy precipitation events over the second half of the twentieth century (Trenberth et al., 2007). Increases in heavy precipitation events have been observed even in regions where total precipitation depths have decreased, implying an increase in precipitation intensity (IPCC, 2008). These changes in intensity have lead to an increase in the risk of pluvial flooding in some regions (IPCC, 2012). This has been observed within the Midwest of the United States where an increase in the frequency of heavy rainfall days has been observed despite oveall rainfall depths remaining constant, suggesting that changes in the magnitude and frequency of floods are occurring at regional scales (Mallakpour and Villarini, 2015).

These trends suggest that the frequency of heavy precipitation or the proportion of total rainfall from heavy rainfalls will increase in the twenty-first century over many areas of the globe. Over the same timeframe, global land use forecasts predict that urban areas will continue to grow (Güneralp and Seto, 2013; Seto et al., 2012). The combined effect of climate and land use change is likely to exacerbate the risk of urban pluvial flooding through increased runoff volumes and more rapid responses due to the growth in impermeable land surfaces (McGranahan et al., 2007).

2.2.3 Changing Climatological Risks

The climate challenges experienced across the globe include heat stress (Trenberth et al., 2007), extreme precipitation (Trenberth et al., 2015), coastal flooding (Jha et al., 2012), and water scarcity (Revi et al., 2014); many of these risks are concentrated in urban areas (Field et al., 2014). In 2001, sixty per cent of urban areas with populations greater than a million people were located in areas at high risk of exposure to at least one type of a natural disaster (UNPD, 2014). Within Latin America, the Caribbean, North America and Asia between one-half and two-thirds of the cities with 1 million inhabitants are exposed to at least one form of natural disaster (UNPD, 2014). In the context of water risks, the World Economic Forum's Global

Risks Report placed four water related impacts on the top ten risks most likely to occur; with 'water crises' listed as the event with the highest potential impact (World Economic Forum, 2015).

Flooding can incur major economic costs, through direct damage, disruption to affected systems, and costs of recovery (IPCC, 2014). As noted earlier, the impacts of global change are already being observed, and cities have already begun to adapt to these new water-related risks. These adaptations aim to defend against increased hydrological variability and challenges to the efficacy of existing water systems. These changes in system performance may occur gradually or in an unexpected manner (IPCC, 2012). To protect cities from growing risks it is necessary to develop adaptive capacity (UN Habitat, 2014). The need for new or reformed urban infrastructure has been highlighted by numerous sources (Geltner and de Neufville, 2012; UN Habitat, 2014). The American Society of Engineers has described the state of American infrastructure as requiring major redevelopment (American Society of Civil Engineers, 2013), while the UK's Institution of Civil Engineers has described the state of Britain's flood infrastructure as in need of significant investment. It has been estimated that 57 trillion US dollars will be required to meet and renew global infrastructure demand worldwide by 2030, with over two-fifths of this amount needed for electricity and water systems (Dobbs et al., 2013). However, the planning and design of appropriate flood defences is complicated by many sources of uncertainty interacting with one another.

2.2.4 Uncertainty Propagation

Changes in the structure, development, and location of global populations are key drivers of greenhouse gas emissions, which in turn dictate the level of climate change that will be experienced (Kjeldsen and Rosbjerg, 2004; Stainforth et al., 2007). These developments are affected by implementing environmental regulations, economic investment in clean technologies, and population growth. However, these factors are extremely difficult to accurately predict due to their complex and chaotic nature.

The effects of these greenhouse gas emissions are translated to potential changes in the climate through the use of Global Circulation Models (GCMs). The IPCC recognises three main sources of uncertainty in GCM projections: uncertainties in identifying and replicating natural variability in the climate; uncertainties in climate model parameterisation and structure; and uncertainty in future carbon dioxide concentrations (Kirtman et al., 2013). The outputs of Global Circulation Models can diverge considerably due to how the climate change signal is identified from noisy climate data. Due to this, GCMs are not extremely sensitive to different emissions scenarios in the near-term future. However, GCM results concerning the end of the twenty-first century are dominated by model and emissions uncertainties (IPCC, 2012). Lastly, there remain a number of unknowns in climate modelling; Knutti and Sedláček (2012) found that despite better process understanding, there is little evidence from the Coupled Model Intercomparison Project (CMIP5) that the ability to model large-scale climate feedbacks has improved significantly from CMIP4.

Despite this, GCM projections are broadly in agreement on how global averages will change. At regional scales there is disagreement between GCMs on the magnitude and in some cases the direction of change that may occur (García et al., 2014). This is particularly true with regards to precipitation patterns (Schewe et al., 2014). Probabilities of potential future events can be generated by running ensembles of these models; however the accuracy of these probabilities are dependent on their ability to accurately reflect real life dynamics. Despite their shortcomings, GCMs remain the best class of models on which we can rely to predict future climatic change. Other models allow for a more integrated assessment of climate change impacts, but these models are still reliant on GCMs for climate projections (Carter et al., 2007).

Global Circulation Models generate outputs at coarse temporal and spatial resolutions. One grid cell may encapsulate several countries or regions while the temporal resolution may be on an annual scale. Urban flood models however perform best with input data at sub-hourly resolutions and at a local scale (IPCC, 2012). Urban rainfall runoff models therefore rely on downscaling to increase the spatial and temporal resolution of results from the large-scale climate models. However, both statistical and dynamical downscaling methods are limited in their ability to deliver useful information if the GCMs are not in agreement. The downscaling procedure itself adds a further level of uncertainty. Downscaling utilises historically observed relationships to transform global or regional projections to information relevant for a specific location (Kirtman et al., 2013). In the context of climatic non-stationarity it is not clear whether this predictor-predictand relationship will remain valid in the future (Milly et al., 2008).

2.2.5 Deep Uncertainty

Infrastructure systems have design lives which can extend to two hundred years in length (Hallegatte, 2009). Due to the length of such design lives there is a high degree of uncertainty surrounding the future conditions under which these systems will operate and whether infrastructure decisions made in the present will remain relevant in the future. These long term decisions are undertaken within a context of deep uncertainty (Hallegatte et al., 2012). Generally speaking, decision makers are either unaware of the presence of deep uncertainty or are not familiar with how to manage it. This has resulted in DMDU not entering the mainstream of climate change adaptation.

Deep uncertainty is defined as 'when the parties to a decision do not know – or agree on – the best model for relating actions to consequences or the likelihood of future events' (Lempert, 2003, pp.3). This may result in a situation where the direction or magnitude of change may be unknown (Regos, 2012). Walker et al. (2013) built further on this definition by stating that deep uncertainty occurs when decision makers cannot agree upon the appropriate framework to model the system including the statistical distributions of key parameters, the sources of uncertainty, and how to rank the possible strategies generated.

Hallegatte et al. (2012) stated that there are three factors that need to be addressed in the context of making decisions under deep uncertainty: 1) Knightian uncertainty (Knight, 1921); 2) multiple valid potential futures; 3) and decisions must be considered with path dependence in mind, meaning that the order in which solutions are implemented has an effect on system efficacy.

It is critical to note that deep uncertainty does not reflect a state of complete ignorance about the future. It is possible to generate plausible states of the world, as visualised in Figure 2.1

and potentially rank them in order of likelihood (Kwakkel and Pruyt, 2013). However it is extremely difficult to explore all possible uncertainties and futures (Herman et al., 2014).

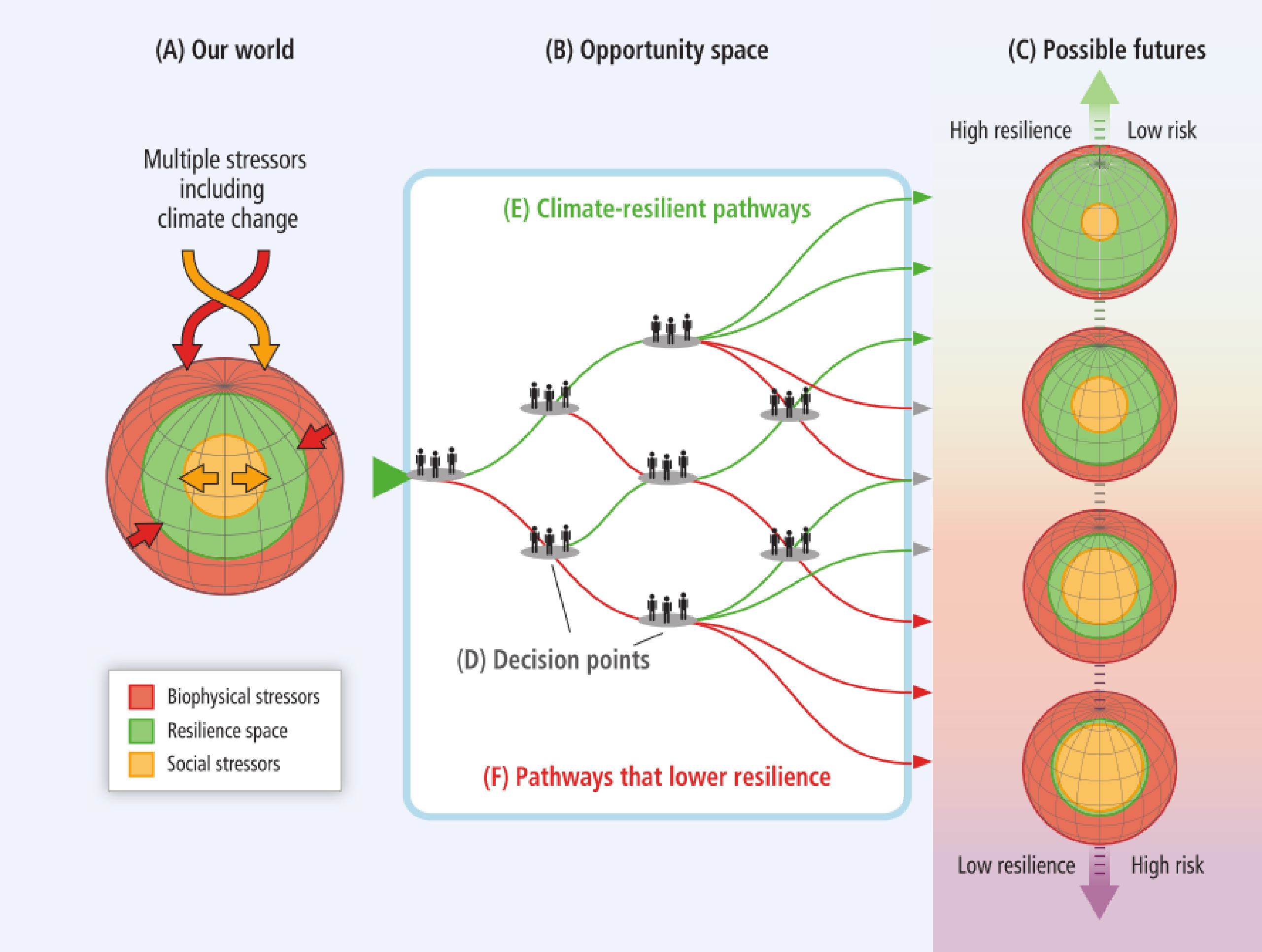


Figure 2.1: Visualising multiple potential pathways to the future (Field et al., 2014)

In the context of urban flooding multiple sources of uncertainty are introduced through climate change, land use change, population growth, and the availability of future capital to maintain systems. Together, these uncertainties exhibit the properties of deep uncertainty delineated above. Given the uncertainties surrounding projections only a limited degree of confidence can be placed in the ability to predict the future state of these systems. Therefore, planning methodologies must account for these uncertainties as traditional optimum design is not appropriate to address decision challenges with the characteristics of climate change (Groves and Lempert, 2007).

The discussion of Decision Making under Deep Uncertainty requires a highly specific vocabulary. Due to the importance of specificity when discussing abstract concepts such as multiple potential futures. To complicate things, many of these terms are inter-related and similar to one another but slightly different. Table 2.1 outlines the definitions of terms used throughout this thesis.

Table 2.1: Definitions of Key Terms

Term	**Definition**
Reliability	The level of service a system is expected to deliver in relation to an event occurring.
Scenario	A hypothetical future used to explore how a system will respond to potential future events.
Robust	The range of potential scenarios within which a system or adapted system can deliver a reliable level of service.
Risk	The impact of an event multiplied by the probability of that event occurring.
Resilience	The ability of a system to return to normal conditions after it has failed.
Adaptation Strategy	A single or collection of potential adaptations that could be implemented.
Adaptation Pathways	A set of incremental adaptations that will allow the current system to be adapted up to a given planning horizon.

2.3 Adaptation to Change

2.3.1 Current Methodology and Limitations

The standard method of designing infrastructure is to utilise models to predict the most likely future and generate infrastructure design to operate in this future (de Neufville and Scholtes, 2011). In the context of urban flooding, this approach generates a flood defence scheme tailored to what the forecast predicts is the 'most likely' future. This methodology is generally referred to as 'predict then act' and is usually reliant upon historical data. This method follows the steps laid out in Figure 2.2.

There are two main issues with this approach. Generally, future projections are based upon or to a great extent utilise historical data with the assumption that the future will continue to look significantly like the past (Rahman et al., 2008). However, the effects of climate change are

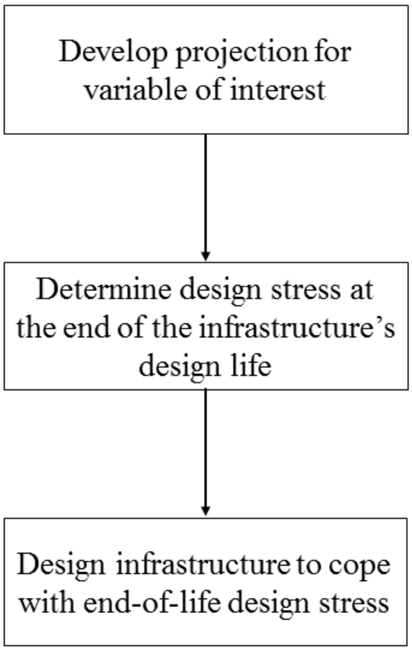


Figure 2.2: Predict-then-Act methodology

such that Milly et al. (2008) declared the death of meteorological stationarity. Due to this non-stationarity, Brown (2010) noted that many of the assumptions made about infrastructure have been made void or will be made void in the future, leading to end of reliability. In addition, predictions of the probability distributions of future variables may have high variances and 'fat tails' (Taleb, 2012). The presence of fat tails results denotes relatively high probabilities of extreme events occurring. Given that the effectiveness of flood defence strategies can deteriorate rapidly if small deviations occur from the projected climatic conditions these errors in prediction can lead to systems which deliver inadequate levels of flood protection. Traditional optimised systems perform well across a narrow band of conditions. McInerney et al. (2012) noted that this was similar to 'dancing on the top of a needle', as such, systems tend to experience very rapid declines in performance when conditions are outside of this narrow range of conditions.

Within the predict-then-act paradigm there is very limited recognition of uncertainty; this is caused by overconfidence in projections of the future (Slovic et al., 1981). These predict-then-act methods are effective when uncertainties about the future are small and well characterised. However they are generally inadequate for the long term planning of open systems such as urban drainage systems. The limitations of static, highly optimised plans are already being exhibited. Climatic uncertainty, coupled with growing urban demands from consumers and legislation, has been shown to pose challenges to the success of water agencies' plans (Groves et al., 2008). For example, the 2001 master plan to mitigate flooding in Ho Chi Minh City had to contend with higher than expected increases in peak rainfall that occurred between the design and final implementation phase of the master plan (Jha et al., 2012).

In the past, to compensate for the uncertainty surrounding future conditions, infrastructure was designed to be more robust. This can be achieved by adding factors of safety; however, this can impose a large financial cost. The accelerating rate of change highlighted earlier also exacerbates the problem of how large this factor of safety should be. Furthermore, solutions can be designed to a return period such that there is only a remote change that this design event can be exceeded. However, as noted earlier, such estimations are prone to errors, and only a limited degree of confidence can be placed in them.

2.3.2 System Attributes

It is becoming increasingly evident that the use of optimal, but otherwise fragile strategies is not appropriate for an uncertain future. Strategies for the future must be robust, there are two variations of this: static and dynamic. Static robustness defines the range of possible futures within which a system can deliver a desired level of reliability (Matalas and Fiering, 1997). More simply, this is the ability to withstand a wide range of shocks, usually developed by utilising factors of safety and layers of redundancy. However, this strategy can quickly become prohibitively expensive. Alternatively, dynamic robustness can be utilised; this method emphasises a system's ability to adapt to changing conditions. However this form of robustness requires a high degree of pro-active management of the system (Herman et al., 2015). A dynamically robust approach emphasises learning and iterative decision-making in order to develop improved system understanding and re-evaluation of the system.

It is critical to make a distinction between reliability and robustness. Reliability is focused upon the expected performance level of a system. Robustness is centred on the range of potential futures that a strategy is able to deliver reliability. Adaptation strategies aim to maintain a given standard of reliability, however, the strategies to achieve this level of reliability can be either robust or fragile depending on the strategies' response to potential changes.

2.4 Decision Making under Deep Uncertainty Methods

Decision Making under Deep Uncertainty (DMDU) techniques offer insights on how to mange the potential impacts of change as opposed to predicting future conditions (Walker et al., 2013). DMDU can be thought of answering 'What if?' questions as opposed to 'What will happen?' questions. The approach acknowledges that there are many potential futures and that a given standard of reliability must be achievable for all of them (IPCC, 2014). DMDU techniques tend to result in strategies which result in multiple adaptation pathways (Haasnoot et al., 2012), the postponement of decisions till more knowledge is available (Zhang and Babovic, 2012), emphasise creating and maintaining system flexibility (Deng et al., 2013), and iterative risk based decision-making to achieve these goals (de Neufville and Scholtes, 2011). DMDU techniques have been applied to water supply issues in the past (Matrosov et al., 2013); however, they have not been widely used in flood management.

Generally speaking, DMDU techniques utilise exploratory modelling to facilitate the identification of robust strategies. In exploratory modelling the effects of variation on key parameters are investigated. This results in a large number of computational experiments with each one representing a hypothesis about what may occur in the future. From this ensemble of potential futures it is possible to ascertain which policies perform well across multiple futures. Exploratory modelling is useful in identifying behaviours which are general and which are specific to combinations of parameters, the validity of key parameters, and modellers' biases (Mackay and Mckiernan, 2004). There are a number of methods to perform exploratory modelling, generally speaking, the more expansive and thorough the exploration, the greater the computational power required.

Within the context of urban flooding, there are a number of DMDU techniques that can be applied. Walker et al. (2013) provides a comprehensive summary of decision-making under deep uncertainty approaches. A brief summary of the relevant model-based methodologies applicable to urban flooding problems is presented in more detail below.

2.4.1 Robust Decision Making

Robust Decision Making (RDM) can be thought of as stress testing a given strategy through the use of many model runs (RAND, 2013). In a RDM analysis the current system is modelled and its performance evaluated across numerous potential futures. A meta-analysis can then be performed on these scenarios in order to identify which are the key parameters that result in failure. Once these vulnerabilities are known, potential vulnerability reducing measures can be suggested, delivering a solution that performs adequately across all or most of the futures generated (Lempert et al., 2013b). The process can then be repeated on the more robust system; this iterative process 'enables systematic quantitative reasoning about the consequences of and trade-offs among alternative decision options using multiple values and multiple expectations about the future' (Lempert et al., 2013b, pp. 10). The methodology is further clarified in Figure 2.3. As such, the goal of RDM is to seek strategies whose performance is less sensitive to the most significant uncertainties.

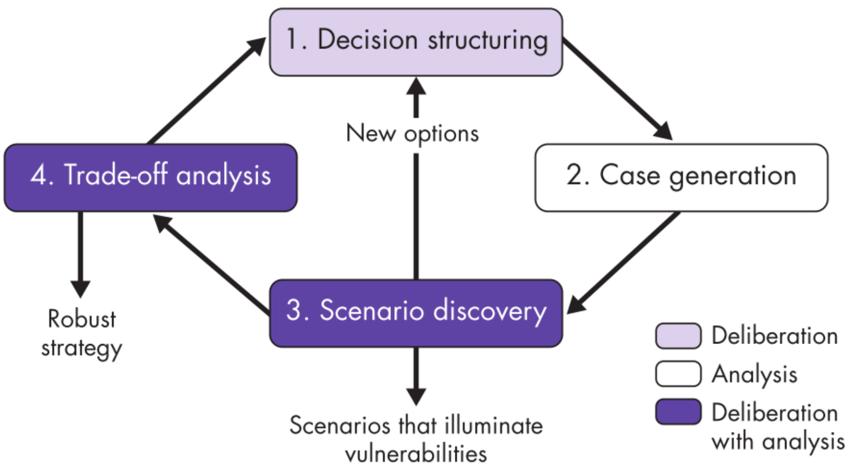


Figure 2.3: Methodology to conduct a RDM analysis (RAND, 2013)

Robust Decision Making eliminates the need to identify a set of scenarios which are felt to describe all potential futures before performing the analysis (Herman et al., 2014). Robust

Decision Making may be computationally expensive depending upon the computational cost to simulate a single future and the number of futures explored; the load is exacerbated by the number of policies evaluated and the number of iterations of analysis undertaken. Scenario discovery allows for the identification of which range and combination of variables policies experience failure (Groves and Lempert, 2007; Lempert et al., 2013a, 2006). This can be achieved through the use of Classification And Regression Tree (CART) (Agusdinata, 2008) or the Patient Rule Induction Method (PRIM) (Matrosov et al., 2013). This results in a small number of discrete scenarios which together should adequately represent all potential futures. A global optimisation evolutionary algorithm may be used if there are many trade-offs between planning alternatives, this is known as Many-Objective Robust Decision Making (Kasprzyk et al., 2013).

Within the context of urban flood risk management a Robust Decision Making analysis was performed for the urban drainage system of Ho Chi Minh City (Lempert et al., 2013b). The city relies on a significant amount of legacy infrastructure and there was a need to investigate the system's ability to handle future population change. The system was stress tested using the Surface Water Management Model (SWMM), against 1,000 potential futures based upon six uncertain parameters. Six potential strategies were assessed with success measured by the economic losses caused by a design storm.

2.4.2 Adaptation Tipping Points & Adaptation Pathways

Adaptation Tipping Points (ATP) is a method of adaptation planning in which a system is modelled and then placed under increasingly large stresses in order identify when the system will no longer be able to deliver a desired level of reliability. This level of stress is known as an Adaptation Tipping Point. The desired reliability level is generally defined through the use of national standards and legislation. Adaptation Pathways builds upon the Adaptation Tipping Points approach by identifying when the current system will fail, identifying potential adaptations to the system, and re-performing the ATP methodology on the adapted system (Kwadijk et al., 2010). This results in a set of potential adaptation pathways. The conditions under which an ATP will occur may be transformed into an estimate of when it is likely to occur, known as a 'sell by date' through climate projections (Haasnoot et al., 2012). This methodology is visualised in Figure 2.4. Within this planning methodology the effects of forecasting errors are secondary to the physical processes that might occur in the catchment.

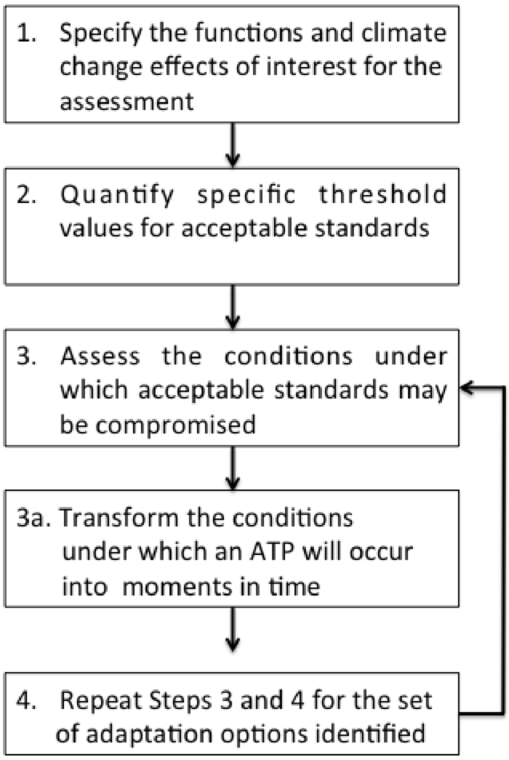


Figure 2.4: Adaptation Tipping Points methodology, adapted from Kwadijk et al. (2010)

The benefit of the ATP methodology is that it is virtually independent of climate change scenarios, and the probabilities of climate change. The method is based on potential changes and the effects of these potential changes on the studied system; the probability associated with a certain level of climate change occurring is secondary to the impact it may have. Combining the ATPs with information from projections provides information about the robustness of systems by giving an indication of how soon in the future an ATP may be reached.

Adaptation Pathways, such as the example shown in Figure 2.5 are used to communicate the results of an DMDU analysis to decision makers. These pathways communicate under which conditions certain strategies are effective, and the logical order in which adaptations should be implemented. The presented example also communicates potential opportunities to switch strategies and an estimate of when these events will occur. The colours act to differentiate between pathways and do not convey any additional information regarding the Adaptation Pathways. Such pathways allow for path-dependence to be considered, as earlier decisions influence potential future adaptation strategies, in doing so the pathways facilitate low-regret decision-making. Additionally, the solutions developed will be area-specific, allowing for a high degree of stakeholder engagement. The analysis is most easily applied to changes resulting from a single driver, however, in actuality there are likely to be a combination of drivers of change.

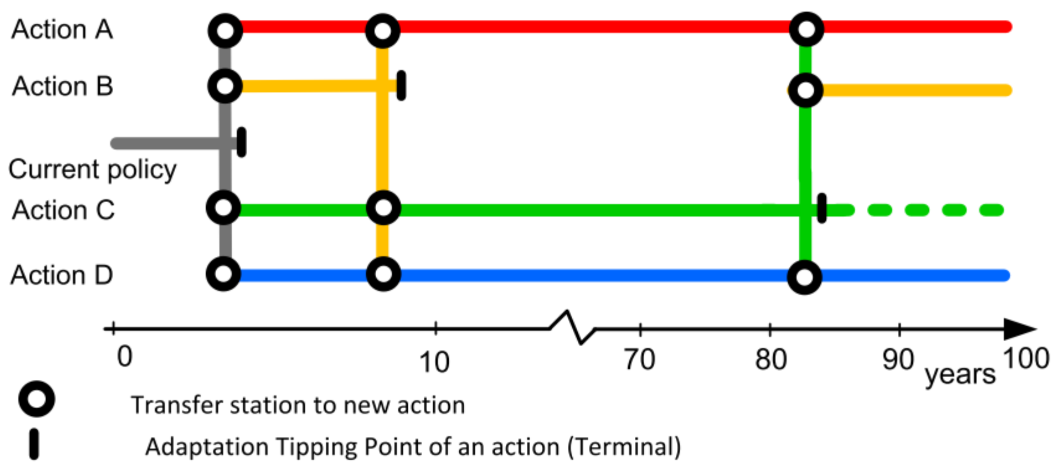


Figure 2.5: Example Adaptation Pathways, the colours signify varying adaptations that could be implemented (Haasnoot et al., 2013)

The ATP method was used by Gersonius et al. (2012) to analyse a storm drainage system in Dordrecht, the Netherlands. The design storm's rainfall intensity for the drainage system was increased until the system failed to perform to national standards. The performance of Dordrecht's existing drainage system was found to remain acceptable for up to a 30% increase in rainfall intensity. When compared to the worst-case climate change scenario generated by the Dutch climate office, this ATP was not expected to be exceeded until after 2100. Another prominent example of the application of ATP method is the Thames 2100 study, which was utilised to identify potential flood defence measures along the Thames estuary (Ranger et al., 2013). The Thames estuary was modelled and the sea level incrementally raised to identify when to implement new coastal defence measures. This resulted in an incremental strategy to protect against sea level rise.

2.4.3 Dynamic Adaptive Policy Pathways

Dynamic Adaptive Policy Pathways (DAPP) is an amalgamation of the Adaptations Tipping Points methodology and Adaptive Policy Making, a high-level framework for decision-making (Kwakkel et al., 2010). DAPP is an emerging planning paradigm that aims to develop dynamic plans, allowing systems to adapt over time (Swanson et al., 2010; Walker et al., 2001; Hallegatte, 2009). This methodology is particularly useful for systems that experience large uncertainties and where highly divergent futures are possible.

The DAPP method identifies gaps in reliability that may occur and actions which address these gaps in a manner not dissimilar to the ATP approach. These gaps are utilised to develop potential adaptation pathways and preferred pathways. These pathways can be evaluated and their robustness assessed through the use of many computational experiments. The analysis of plausible actions is complicated by the fact that plans should be adapted over time. This entails analysing potential adaptations across a planning horizon rather than one moment; this allows for the effects of staged decision making processes to be replicated within the framework (Haasnoot et al., 2013). Once the planning is completed, a Dynamic Adaptive Plan is then put into place with the objective of monitoring the system under study and maintaining flexibility of choice between pathways for as long as possible. This methodology's components are visually summarised in Figure 2.6.

DAPP requires the generation of many simulations to identify gaps in reliability, identify solutions to address those gaps and conduct the assessment of the pathways. As most hydrological models are too computationally expensive to be applied in this context, it is recommended that simple and faster models are utilised when under taking a DAPP analysis (Kwakkel et al., 2014).

Within the context of flooding the DAPP method was used to model a flood defence scheme in the lower Rhine (Haasnoot et al., 2013). The final output of this approach was a set of robust candidate pathways. The results of the study suggest that by providing a set of potential pathways and through integrated local monitoring, decision-making processes can focus upon

Figure 2.6: Methodology to conduct a DAPP analysis, taken from Haasnoot et al. (2013)

choosing and updating appropriate plans of action such that options remain open to future developments.

2.4.4 Discussion & Recommendations

As shown in Section 2.2, urban drainage systems are exposed to many interacting, cascading, and accumulating uncertainties. The resulting deep uncertainty leads to a state of ambiguity regarding future conditions. Traditional methods of infrastructure design such as 'predict then act' also known as 'top-down' approaches revolve around making decisions based on accurate forecasts. However, limited trust can be given to forecasts regarding systems such as cities or the climate as they are both open and complex adaptive systems. In order to improve urban pluvial flood planning and build future-proof infrastructure designers and engineers should focus on how drainage systems or potential adaptations will react to potential changes. This is a fundamental shift in the way infrastructure is designed. The Decision Making under Deep

Uncertainty paradigms analysed all acknowledge this and utilise a 'bottom up' approach. While all DMDU methods use a bottom up approach they perform their analysis in slightly different ways. The different methods are summarised within Table 2.2.

Table 2.2: Summary of DMDU Methods

Method	**Principle Objective**	**Description**	**Flooding Example**
Robust Decision Making	Strategy that operates reliably under a range of scenarios	Strategy's performance evaluated against a portfolio of scenarios	Lempert et al. (2013b)
Adaptation Tipping Points	Incremental adaptations to changing circumstances	System incrementally loaded till failure is reached	Gersonius et al. (2012)
Dynamic Adaptive Policy Pathways	Iterative decision making over time	Explores a variety of uncertainties to connect short-term targets to long-term goals	Haasnoot et al. (2013)

The choice of which DMDU framework to use should be decided by how pro-active the urban drainage system's management body is. Robust Decision Making has a tendency to generate solutions that are more statically robust than the other frameworks presented. This has the benefit that solutions can be constructed and then require minimal management. In this approach there might be a larger capital cost initially but little operational management is needed. Alternatively, Adaptation Tipping Points and Dynamic Adaptive Policy Pathways place a greater deal of emphasis on monitoring the drainage system and performing iterative decision-making. In such a framework solutions are implemented only when needed and the individual adaptations could be more incremental in nature than one suggested by a RDM analysis. The choice between ATP and DAPP should be made after formulating the problem. If a problem involves many different or diverging stakeholders or influencing factors then DAPP is more applicable as it is more adept at resolving these contradicting factors.

Regardless of the selected approach, the application of a DMDU framework requires a larger computational investment than typical design methods in order to assess how the modelled system may react to potential changes. To better mange these large ensembles of simulations the urban drainage community requires an improved understanding of how to utilise the emerging developments in high performance computing, cloud computing, and parallelisation to their advantage. To reduce computational load trade-offs may be made between model run time and the degree to which physical processes are replicated. What is the appropriate trade-off between these factors remains an open question and there is much to investigate specifically with regards to model choice.

With respect to modelling, existing urban flood tools are in theory appropriate for use within DMDU applications. Many models can deliver varying levels of fidelity with regards to mesh size, semi or fully distributed physics, and one/two dimensional surface flows. However, for the purposes of Decision Making under Deep Uncertainty analyses these models will require improved interfacing with control functions to better manage the results of hundreds of model runs. Depending on the scope of the urban drainage problem, these models will also need appropriate Application Program Interfaces (API) to interact with external modules such as land-use or economic models. These additions will greatly improve the speed and ease with which these analyses can take place. The computational load and organisation of these computational experiments will greatly add to the workload of the team that generates the design of the urban adaptation. This workload is further exacerbated by the need to engage with stakeholders in order to develop catchment appropriate solutions.

DMDU frameworks are most effective when there is broad stakeholder engagement. This is especially critical at the beginning of the assessment when structuring the problem. Perhaps most importantly it is critical that the stakeholders come to a definition of success or failure. Within an urban drainage problem, the specific stakeholders that should be involved in the planning process will differ depending on the division of ownership and responsibilities for each locality's drainage system. However it would be safe to assume that the local governmental authority, the local drainage authority, and local residents or businesses would be consulted in the vast majority of cases. The coordination of these stakeholders would best be undertaken by whoever is responsible for the design of infrastructure so that these views can be taken into account during the analysis. Upon the completion of the DMDU analysis the design team would then re-convene the stakeholders in order to effectively communicate the costs and benefits of the potential strategies that may be implemented. Based upon these stakeholder consultations a strategy would be chosen and then constructed. The issue of cost must be addressed as well, however this has not be explored to a large extent beyond (Woodward et al., 2014a,b).

2.5 Conclusions

Based on the discussion above, it is clear that urban drainage planning is exposed to deep uncertainty. The application of Decision Making under Deep Uncertainty frameworks and techniques offers the potential to solve the cities. This is especially true given the highly dynamic urban climate era that is currently taking place. DMDU will allow for the continued reliability of systems despite the highly uncertain future ahead. The need for strategies to cope with deep uncertainty is clear and can be championed by many parties such as the government or the local community. However, the task and responsibility of applying these techniques resides with the practitioners of and researchers of the urban drainage community.

The intersection between urban drainage planning and Decision Making under Deep Uncertainty is a young field and there remain many open questions and opportunities for further work. These include questions regarding model structure and the problem formulation for urban drainage contexts. There is much to explore with regards to the applicability of blue-green infrastructure to problems of deep uncertainty; these questions are explored in Chapter 5. The costing of Adaptation Pathways under uncertainty has not be explored to a large degree. This is a critical issue that must be addressed in order to better inform decision makers. This issue touches upon numerous subjects including the valuation of ecosystems services, flood damage estimates, and the valuation of projects under uncertainty.

Chapter 3

Antifragility and the Development of Urban Water Infrastructure

3.1 Introduction

Antifragility is a property of a system that results in the system becoming increasingly resistant to the external shocks to which it is exposed. These systems have the counter-intuitive property of benefiting from uncertain conditions. This chapter presents the first known applications of antifragility to water infrastructure systems and outlines the development of antifragility at the city scale through the use of local governance, data collection and a bimodal strategy for infrastructure development. This chapter outlines several important concepts within this thesis: that hydrological risks are asymmetric and this asymmetry may create opportunities to be seized. The antifragility framework builds upon the previous chapter by proposing a new framework well suited to dealing with deep uncertainty. This chapter is based upon the paper Babovic et al. (2017), published in the International Journal of Water Resources Development. The systems architecture presented results in a management paradigm that can deliver reliable water systems in the face of highly uncertain future conditions.

In recent years there has been a large increase in the use of sensor networks within urban areas to facilitate data collection in a shift towards the implementation of smart cities. The information collected through the 'Smart City' paradigm can be extremely beneficial in informing local decision-makers on the state of the systems they manage. This work postulates that the Smart City concept lends itself to cities becoming antifragile to climatic and weather shocks over time. By empirically grounding policy-making and adaptation it is possible for cities to become increasingly resistant to the effects of extreme weather conditions over time. This continual evolution is a central pillar of the concept of antifragility. Antifragility is a system property originally detailed by Taleb (2012), antifragile systems become increasingly resistant to external shocks by being exposed to them. This property results in such properties benefiting from uncertain conditions. The development of antifragility in urban water systems will lead to an increased capacity to adapt to the shocks and stresses they will be exposed to in future. This chapter introduces the use of the concept of antifragility to guide infrastructure planning and management in cities. There is only one known instance of antifragility having been applied to infrastructure planning (Bruce Beck, 2013). This paper also discusses how urban water systems can be managed to achieve antifragility.

3.2 Water Issues in Urban Areas

3.2.1 Changing Urban Water Challenges

As noted in Chapter 2 the world is experiencing an extremely rapid rate of change across a spectrum of issues (Friedman, 2008). In large part these changes are driven by the rapid and continued rise of the urban population of the globe which has grown from 746 million people in 1950 to 3.9 billion people in 2014 (United Nations Department of Economic and Social Affairs Population Division, 2014).

Urbanization leads to higher demand for natural resources, particularly for water. Additionally, the relative wealth of urban residents leads to increased water demand through water-heavy goods and widespread use of white goods (ARUP, 2014). These trends have been observed in Australia where growing cities have increased their water usage fivefold through both population growth and increased demand for water-heavy goods (IPCC, 2014). Similar phenomena are occurring across the world, with half the world's cities with more than 100,000 inhabitants experiencing water scarcity (ARUP, 2014). Concurrently, climate change is changing hydrological conditions across the globe. Climate change is projected to exacerbate desertification and water stress through reductions in incident precipitation and by altering snowmelt patterns (IPCC, 2014). This is resulting in negative effects on agriculture and business in some regions (UN-Habitat, 2014). In turn, these developments have led to increased reliance on groundwater, leading to lower water tables and an increase in the number of incidences of saltwater intrusions in coastal aquifers (IPCC, 2012).

On the opposite end of the hydrological spectrum changes in precipitation patterns have resulted in growing pluvial flood risk. The IPCC's Fifth Assessment Report found that the number of heavy precipitation events across the globe have increased in the last 50 years (Trenberth et al., 2007). These increases in heavy precipitation events have occurred even in regions which have become increasingly water stressed over time. The increase in precipitation intensity lead to the growing risk. It is predicted that these heavy rainfalls will contribute to increased levels of flooding in certain catchments and regions (IPCC, 2008, 2012).

The increasing exposure of people and economic assets to weather-related impacts has been the major cause of long-term increases in economic losses from climate disasters (Jha et al., 2012; IPCC, 2014; World Economic Forum, 2015).

In the face of these growing hydrological extremes, new infrastructure must be built or existing infrastructure adapted (Geltner and de Neufville, 2012; UN Habitat, 2014). In the developed world, there is a need to renovate much existing infrastructure. As noted in Chapter 2 it has been estimated that US$57 trillion will be required to meet global infrastructure demand worldwide by 2030, with over two fifths of this amount needed for electrical and water infrastructure (Dobbs et al., 2013). The sheer length of the design lives of such infrastructure systems result in the decisions relating to infrastructure planning being exposed to conditions of deep uncertainty (Hallegatte et al., 2012)

3.2.2 Deep Uncertainty and Predictive Errors

Under conditions of deep uncertainty, the uncertainty surrounding the future cannot be significantly reduced through intensified data collection as the past is of limited use as an indicator of future conditions (Milly et al., 2008; Walker et al., 2013). In the context of urban water management, multiple sources of uncertainty are associated with climate change, population growth and per capita water use. Given the limited level of confidence that can be given to long-term predictions, is critical that planning methodologies account for these uncertainties as traditional design methods are not appropriate ataddressing decisions with the characteristics of climate change (Groves and Lempert, 2007). McInerney et al. (2012) noted that infrastructure systems are optimized to operate under very specific conditions akin to 'dancing on the top of a needle'. These systems are fragile to situations whereby small deviations between predicted and actual conditions can result in large deteriorations in system performance. Developing systems that operate well under a narrow range of conditions requires a high level of confidence in the future state of the world. This level of confidence is, generally speaking, not possible to achieve for open systems (Taleb, 2012).

While Taleb (2012) does not utilize the phrase 'deep uncertainty, it can be argued that he is in broad agreement on the presence of deep uncertainty and its underlying causes. Taleb's work focuses on the use of historic data as the basis for making assumptions, with an emphasis on the historical record's inability to properly characterize the tails of probability distributions. This results in a poor ability to accurately assess the probabilities and risks associated with extreme events. This has partly been reflected in modellers' poor track record of making accurate long-term predictions for complex systems. This lack of predictive ability stems from what Taleb termed the 'extended disorder cluster'. This cluster broadly reflects the various facets of uncertainty delineated by Walker et al. (2003) as epistemic or aleatory uncertainties.

The accurate prediction of when events, especially remote-probability events, will occur remains a significant challenge. However, the knowledge to build systems that can withstand these remote-probability events is much more developed. As Taleb (2012, p.136) notes, 'Not seeing a tsunami or an economic event coming is excusable, building something fragile to them is not.'

As noted in the Literature Review cities require continual re-invention of their urban water systems in order to manage growing extremes and changing conditions. In order to achieve this, the development of infrastructure in urban areas should focus on exposure to failure and the consequences of extreme events (Taleb et al., 2009).

3.2.3 Smart Cities

Proponents argue that the implementation of Smart City technologies would make urban infrastructure and management systems more efficient and cost-effective (Department for Business Innovation & Skills, 2013). The 'concept of the smart city emerged during the last decade as a fusion of ideas about how information and communications technologies might improve the functioning of cities' (Batty et al., 2012, p.483). Under the Smart City paradigm, the data collected through sensors are transmitted via a telecommunications network to storage where they are then analysed in order to adjust urban operational processes. Certain data streams collected from smart cities can be particularly useful when used for the purposes of urban climate change adaptation. To gather this data the data-collection system would take the form of weather data-collection apparatuses along with sensors used to quantify system response. The data collected by these sensor networks would allow for the identification of how urban water systems perform and the efficacy of management options. A more detailed discussion of the architecture of data collection for an antifragile urban water system is presented below.

3.2.4 Robustness

What is traditionally thought of robustness has been termed 'static robustness' by the Deep Uncertainty community. Strategies that exhibit static robustness aim to reduce the possibility of system failure for the largest range of conditions possible (Buurman and Babovic, 2016; Walker et al., 2013). This is generally achieved by over-dimensioning elements of infrastructure systems to accommodate unexpectedly large shocks or stresses. While this is practically easy to achieve, it can incur significant costs to build over-sized infrastructure. Furthermore, residual risk remains even for infrastructure systems designed to withstand high-return periods. The estimation of the size of remote-return period events is prone to many of the errors highlighted above, including incomplete historical knowledge and a limited degree of confidence in the statistical distributions derived from these data (Milly et al., 2008).

As described earlier, dynamic robustness addresses some of these issues by attempting to adapt systems over time in order to maintain a required level of reliability in the face of changing circumstances. This is similar to the concept of multistage optimization which allows for systems to evolve as new information is made available. For example, sensor networks can be utilized to quantify changing precipitation patterns and then drainage systems can be adapted accordingly. While this method emphasizes a more proactive attitude towards risk management than static robustness, the aim is to maintain a level of reliability rather than continuously build an increasingly robust system.

3.3 Antifragility

Antifragility extends dynamic robustness by providing 'a mechanism by which the system regenerates itself continuously by using, rather than suffering from, random events, unpredictable shocks, stressors and volatility' (Taleb, 2012, p.8). This is akin to the natural world where 'systems subjected to randomness – and unpredictability – build a mechanism beyond the robust to opportunistically reinvent themselves' (Taleb, 2012, p.68). Proposals for similar concepts been made in the past: Bruce Beck (2013) argued that antifragility is similar to Holling's ecological resilience (Holling, 1973), while Liao (2012) proposed that periodic flooding creates opportunities for cities to become better adapted to increasingly extreme floods. Antifragility is a process of continual adaptation as opposed to an end state. When a system is antifragile, accurate knowledge of future conditions is not needed as it would be for a fragile system. For antifragile systems, unexpected shocks offer opportunities for learning and reinvention, resulting in more robust systems.

When antifragile systems experience shocks they 'bring more benefits (equivalently, less harm) as their intensity increase up to a point' (Taleb, 2012, p.2727). This is akin to the body's response to exercise, where imposed shocks lead to improved physical ability. For the fragile,the cumulative effect of small shocks is smaller than the single effect of an equivalent single large shock. This is exemplified by brittle objects which can withstand small loads but experience catastrophic failure once loading exceeds a threshold value. Urban water professionals must ensure that water systems exhibit the desired behaviour.

Antifragile systems are self-healing. This property differentiates antifragile systems from mechanistic systems. After a climate shock antifragile systems overcompensate and adapt to the shock, while mechanistic systems return to their previous state. For example, in order to develop this dynamic, after a shock the local body in charge of the urban water system would assess its performance, identify causes of failure, and modify their systems appropriately. In doing so, the system becomes better at coping with climate variability as it has the property of improving with shocks rather than merely resisting them (robustness) or quickly recovering from them (resilience). This is similar to the concept of adaptive capacity, however adaptive capacity only encapsulates the exploratory, risk seeking half of an antifragile strategy.

Antifragile systems are conditioned by the frequency and magnitude of the shocks to which they are exposed. They respond more positively to acute shocks than chronic stressors, particularly when these shocks are followed by ample time for the system to recover and reorganize. Critically, antifragile systems are not immune to events of all sizes; they can fail if they are affected by an event of sufficient magnitude. However, events below this threshold are treated as opportunities for growth and development. Urban areas can become antifragile when they seek to learn from shocks and the system's response. In doing so, the experience gained by the system managers can be utilized to prepare and compensate for climate shocks. The question remains however: how does one translate the notion of antifragility into the domain of infrastructure planning? The development of antifragility occurs at two levels: the first at the city scale, the second at an informational level.

Both varieties of antifragility require local governance of urban water systems. Within any city there are several potential solutions to water problems. The question of which of these strategies should be utilized is best left to local leaders and organizations who have both local knowledge and direct accountability to residents. This bottom-up leadership should be able to guide the adaptation of urban water systems in such a way so as to result in confidence that the systems would be robust to local climatic conditions.

3.3.1 Antifragility for Individual Cities

A barbell strategy or 'bi-modal strategy' (Taleb, 2012) is utilized to generate antifragility. The strategy is characterized by having two elements: one is extremely risk averse, also known as being 'bounded right'; the other seeks to benefit from rare events, but has limited losses – this is referred to as being 'bounded left'. This results in a dual attitude of being robust to negative events and allows one to capitalize on positive 'Black Swans', resulting in antifragility. The behaviour of these properties is illustrated in Figure 3.1. Where x is the magnitude of an impact acting upon a system and F(x) the response of the system to the impact.

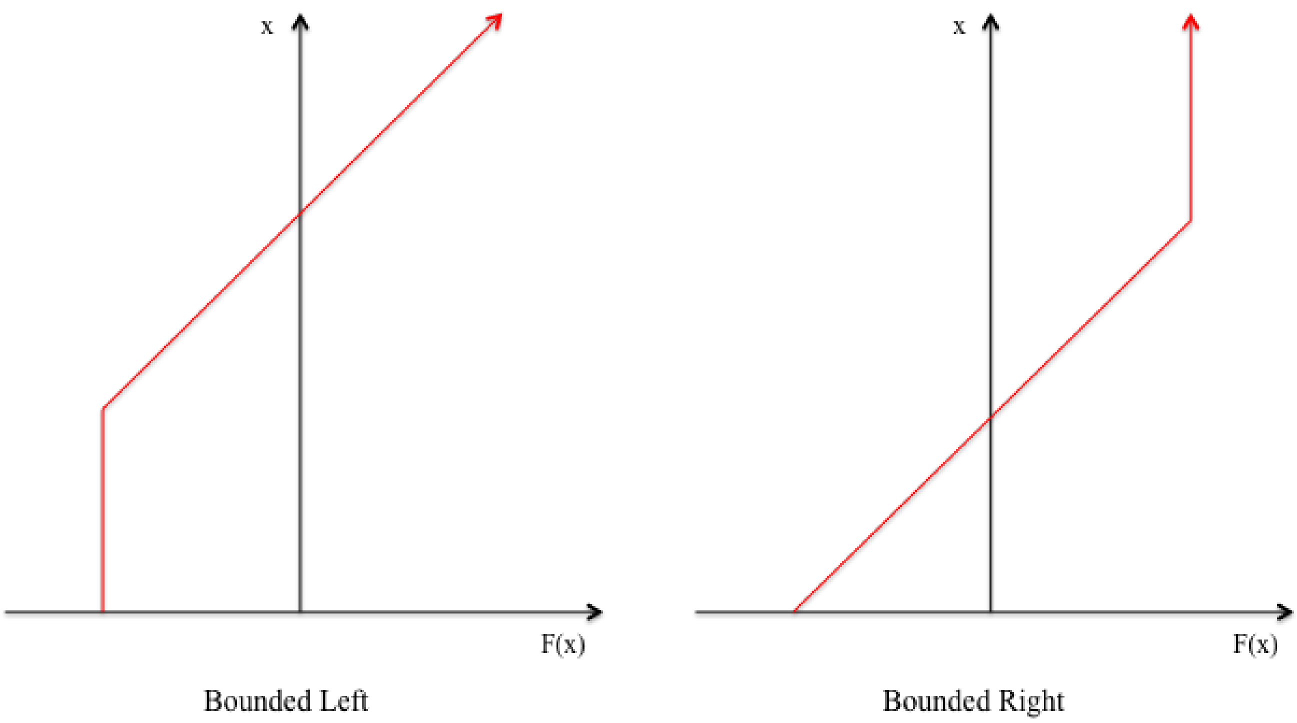


Figure 3.1: Behaviour of bounded left and bounded right systems. x is the magnitude of an impact acting upon a system, F(x) represents the system's response to the impact.

Bounded Right

There are three factors to be controlled in order to achieve risk averseness: size, concentration, and speed of failure (Taleb, 2012). The management of these factors is very similar to the development of static robustness.

The size of the components within an urban water system should be controlled so as to avoid over-reliance on any single piece of infrastructure. Antifragile systems should be composed of layers of redundancy in order to avoid catastrophic failure. For example, an antifragile water supply system would not be reliant upon a single source of water and would utilize a diversified water supply system. This would take the form of a set of robust water-resource solutions including household collection, large-scale reservoirs, and reverse osmosis systems. In doing so, the failure of a single water resource system would not result in the inability to deliver water. Such a water supply system would be similar to the one employed as part of Singapore's Four National Taps policy (Tortajada, 2006). For urban flooding, the magnitude of risk can be controlled through the use of multiple drainage solutions acting in unison. Sustainable urban Drainage Systems(SuDs) such as green roofs and porous pavements would act as a distributed solution to reduce the stress on drainage systems. This drainage system, in turn, could drain into localized rainwater storage solutions to help alleviate the flow to be conveyed along central or downstream drainage systems.

High concentrations of risk can result in unacceptable levels of damage, even when only small system failures occur; this is also true in the realm of urban water systems. The purpose of water supply is to deliver sufficient quantities of water to citizens in order to experience a given level of well-being. As such, the concentration of risk is strongly linked to fresh water demand. By reducing the demand for water, it is possible for periods of poor water-resource replenishment to pass unobtrusively. For flooding, with regard to the concentration of risk, two distinctions can be made. With publicly controlled assets and structures it can be ensured that pieces of critical infrastructure such as energy transformers, pumping stations, police stations and hospitals are not concentrated within a small area. This would ensure that flooding would not cause widespread systemic failure. Controlling the concentration of risk that emerges from the concentration of private assets can be more difficult given that certain areas are simply more attractive places in which to reside. The concentration of private assets can be controlled through the planning system, but also through the use of mandatory flood insurance with premiums priced according to flood risk. These premiums can then be used to improve and maintain flood-defence infrastructure as appropriate.

The speed with which failure occurs is of critical importance. Under favourable conditions, optimization occurs, resulting in efficient but more fragile systems. The avoidance of small mistakes may result in making the large ones more severe. This speed of failure could be established utilizing a stress-test methodology, such as the Adaptation Tipping Points approach (Gersonius et al., 2012; Kwadijk et al., 2010; Reeder and Ranger, 2011). The problem of widespread failure is compounded once infrastructure interdependence is considered. While it is envisaged that there would be a diversity of solutions within a catchment, there would also be a diversity of solutions between catchments. Under conditions of drought, some catchments would perform better than others due to differences in meteorological conditions and supply systems. This would necessitate water transfers to alleviate shortage. A catchment with an excess of water could utilize its redundancy and connectivity to sell its water through a water market. This connectivity and responsiveness provides an opportunity for both catchments involved. However, vulnerability occurs when this connectivity is not responsive. Water transfers should be utilized as a means to 'top-up' failures in supply. Permanent water transfers create teleconnections of risk, where a catchment that receives water is reliant upon the weather elsewhere. In the case of Hong Kong, 80% of water is imported from mainland China. Due to this, Hong Kong's water supply is closely tied to weather conditions outside its own borders (Wang et al., 2016). Catchments should attempt to be self-sufficient and utilize the connectivity between each other in order to take advantage of the diversity in systems and hydrological conditions only during times of critical need.

Bounded Left

The infrastructure systems described above, known as 'bounded right', result in a very robust water supply system. Optionality is the agent of antifragility and differentiates antifragile systems from those which are simply very risk averse. An option allows for the creation of antifragility and allows one to benefit from uncertainty without significant cost (Makridakis and Taleb, 2009). For infrastructure systems, this optionality would take the form of real options. Based on financial options, real options give the holder the right, but not the obligation, to perform a task in future. These rely on a relatively small increase in capital investment cost to allow for increased operational flexibility. This translates into the ability to limit the effects of negative conditions (Wang and Neufville, 2004) and take advantage of uncertain ones (Myers, 1984; de Neufville and Scholtes, 2011; Trigeorgis, 1996; Wang and Neufville, 2004). The more flexible the option, the greater the benefit.

Real options have been found to increase the value of a project by up to 30% and to generate positive value for urban water supply and drainage systems (Deng et al., 2013; Zhang and Babovic, 2009, 2012). Optionality has the added advantage of allowing for an accelerated pace of adaptation as significant elements of the option will have been effectively completed in advance. These smaller increments can be built quickly even if they run in parallel across a wide area; operational research has found that it is the size per segment of the project that matters, not the entire project that is the controlling factor for total time to completion (Flyvbjerg, 2009). As optionality becomes increasingly ingrained into urban water systems through maintenance or construction of new infrastructure systems, the speed with which they can be adapted will increase. Additionally, with decisions delegated to the local level, the speed of decision-making should increase, thus improving the rate of adaptation.

Finally, many concepts are more successful in theory than practically. It is critical that a wide variety of small-scale, experimental projects are utilized to help establish which solutions offer the greatest benefits for a given catchment. These projects should deliver positive asymmetries with regards to system knowledge and will help guide climate change adaptation.

3.3.2 Smart Cities, Data, and Evolution

A second variety of antifragility occurs at the informational level. This variety of antifragility is evolutionary and grows by discerning lessons from a catchment's struggle to operate a reliable service in the face of a hydrological shock. The lessons learnt regarding the operation and efficacy of infrastructure during times of hydrological stress should be shared in order for other catchments to modify their policies accordingly. The diversity that exists between the different catchments' urban water systems allows for different strategies to be compared, allowing for the adoption and rejection of strategies based upon their performance.

The Smart City concept allows for the objective measurement of an urban water system's performance. This leads to the generation of very large data sets. The size of the data sets can lead to over-confidence in findings and systems maladapted due to this misplaced confidence. As such, only a modicum of data is needed to guide decisions and test potential strategies, the majority of this data comes from rare adverse events. Therefore, the data-collection apparatus implemented does not need to offer infinitely fine temporal and spatial resolutions. This will reduce the noise present in the data. The data-collection system needs to be structured in such a way that urban water managers are aware of the broader climatological trends and performance of infrastructure within their system. The establishment of climatological trends may require significant amounts of time, however some actionable data will be made available immediately. For example, if a piece of infrastructure is frequently at or near capacity, this would indicate a need at least to begin planning an intervention.

The analysis of these data should aim to establish heuristics that capture the majority of the information content in the data. Of particular importance is identifying which planning assumptions are incorrect and must be rejected. Given the complex nature of urban water systems, establishing causality will prove to be difficult, but may be achieved through tools such as Granger causality which measures the predictive ability of one time-series to forecast another and that has been found to be successful in identifying potential heuristics (Eichler, 2012).

3.3.3 Local Urban Governance

As noted above, the development of an antifragile urban water system should be achieved by delegating management to local government. Local governance is best able to balance engineering knowledge with local residents' desires and needs, thus resulting in a water system suited to local hydrological and social conditions. This allows for the creation of local confidence in urban water systems. By having these systems controlled through local structures,it is relatively easy to maintain direct accountability to citizens.

However, it is clear that currently many if not most cities do not have an appropriate local governance structure for antifragility. Globally, there are substantial differences in the powers and responsibilities that cities have over infrastructure management and procurement. One global survey of cities found that only 56% of cities are the primary leader in controlling their city's utilities (Burdett et al., 2014). For effective management of an antifragile system, the locus of control of water infrastructure would require these powers to be devolved to metropolitan governments. This would also require the transfer of vast amounts of responsibility and management infrastructure needed to operate a modern water system.

Under systems with private water utilities, once local governmental oversight is established, a large degree of cooperation will be required from the utility to put in place a bimodal strategy. The antifragile paradigm in many respects runs counter to the traditional view of optimizing infrastructure procurement. This is because the bimodal strategy requires the construction of very robust infrastructure (bounded right) and real options (bounded left), both of which would increase capital costs and therefore run counter to the paradigm of lean infrastructure procurement.

3.4 Conclusions

The development of antifragility in urban water systems offers a paradigm through which systems can continually evolve to face better the challenges caused by a changing world. This paradigm would result in flood-resistant and water-independent regions that have the ability to trade water and information in order to strengthen the cohort's ability to withstand hydrological stresses.

There are practical difficulties associated with the antifragile model that would need to be addressed for such a system to be applied in practice. The first is that local government would require a degree of control over their water systems that is atypical. Furthermore, the nature of antifragility is such that it is not 'efficient'; antifragility requires infrastructure which is bounded right, resulting in a system more robust and expensive to construct than the current method of 'lean' development. Additionally, infrastructure that is bounded left may be constructed but not utilized for many years or decades, which could be perceived as a failure to make efficient use of capital. Lastly, the antifragile model places a fairly high degree of burden on the local managing organization requiring a much quicker cycle of continual observation, decision-making and acting. However, this model offers significant advantages in dealing with the variable hydrological conditions that are expected to occur in the medium to long-term future.

Decision Making under Deep Uncertainty methods can be used to identify how left or right bounded a particular intervention is. The Adaptation Tipping Points approach would be appropriate to identify these characteristics and implement them as elements of an antifragile strategy. The information collected by the smart city would be used to also inform how close water systems are to reaching their ATPs. Antifragility can then be operationalised by building upon concepts originally developed within the DMDU community.

Chapter 4

Hydrological Modelling Framework

4.1 Introduction

This chapter details the rainfall runoff modelling framework used to conduct a Decision Making under Deep Uncertainty analysis, specifically an Adaptation Tipping Points (ATP) analysis. The chapter describes both the model itself and the modelling procedures used to complete the analysis. In the Literature Review (Chapter 2) it was highlighted that urban drainage problems have not been widely explored in the context of deep uncertainty. As such, existing tools are not optimised for use with Decision Making under Deep Uncertainty planning methods. This chapter seeks to explain in methodological detail how existing urban flooding simulation software (Infoworks ICM) can be utilised within a DMDU context. This chapter provides the foundation for Chapter 5, where the ATP procedure that uses the model described in this chapter is utilised to develop a set of Adaptation Pathways.

The model used within this thesis builds upon the models created, calibrated and validated during the RainGain project. The RainGain project was a European project aimed at improving the simulation of pluvial flooding within urban areas. The case study for this thesis and one of the RainGain case studies is the Cranbrook Catchment. The Cranbrook is located in the North East of London, as displayed in Figure 4.1.

Similar to the majority of neighbourhoods within London, the Cranbrook Catchment is predicted to experience population growth in the coming years. This population growth is likely to lead to increased amounts of development, land use change, and urban creep. These would exacerbate the flood risk by increasing run-off volumes and the speed of catchment response.

The drainage area of the catchment is approximately 910 hectares in size. The main watercourse that runs through this catchment is the Cran Brook, a tributary of the Roding River. This river is approximately 5.75 km in length, and is approximately 99% culverted. In addition to this the Cran Brook is characterized by two lakes which provide storage for storm flows.

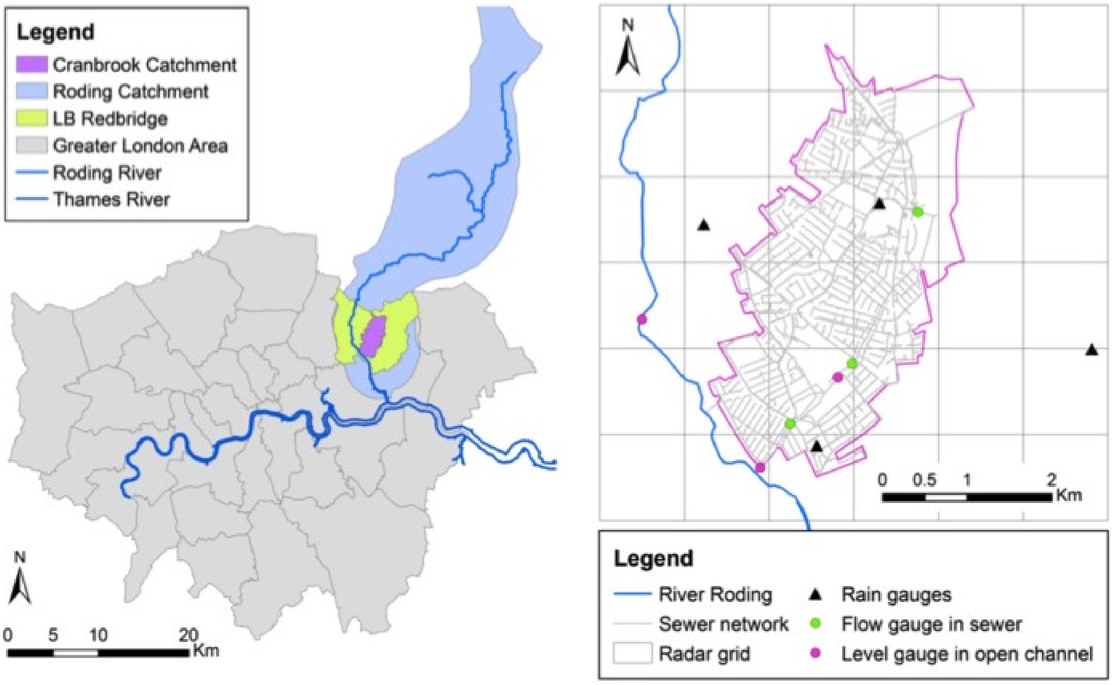


Figure 4.1: Map of the Cranbrook Catchment, from Simões et al. (2015)

The Cranbrook catchment is highly urbanised, 52% of the land cover is impervious. As such, the catchment has a rapid response to rainfall with significant proportions of incident precipitation becoming surface runoff. A detailed map of the catchment can be seen in Figure 4.2. Green dots and lines represent manholes and sewers respectively; the pink polygons indicate buildings in the catchment; and the lakes are the large green areas.

Figure 4.2: Land-use map, green dots and lines represent manholes and sewers respectively; the pink polygons indicate buildings in the catchment; and the lakes are the large green areas.

4.2 Approach to Flood Simulation

A fully distributed Infoworks ICM 1D-2D hydraulic flow model was used to simulate the Cranbrook catchment. The choice of model is expanded upon in Chapter 5. This model was used to identify the Adaptation Tipping Points of potential drainage adaptation strategies under change. The model was originally developed by Pina et al. (2016).

Data from various sources were used to develop the model. The land surface element of the rainfall run-off model was based upon a Digital Terrain Model (DTM) provided by the Environment Agency. The DTM data was collected via LiDAR and is of a $1m$ by $1m$ horizontal resolution. The London Borough of Redbridge provided the locations and polygons of buildings within the catchment. Information regarding the topology of the sewer system, including pipe dimensions and manhole depths was provided by Thames Water.

All 1D-2D urban flood models are composed of two elements; the overland surface model and the model of the sub-surface drainage network.

For fully distributed models the land surface model is defined by a two dimensional overland mesh intended to simulate run-off flows over the ground surface. Within this analysis the land surface model utilised a triangular mesh to simulate surface runoff flows. The irregular mesh consisted of 117,711 elements; the largest mesh was $992m^2$, the smallest was $25m^2$, with the mean mesh size equal to $61m^2$. Fully Distributed models assume that rainfall is directly applied to each triangular 2D element. Runoff volumes for each mesh element were calculated using the NewUK method which utilises information regarding land use, surface storage and infiltration. Infiltration for each 2D element was estimated based on soil saturation and the quantity of run-off present on the land surface. Upon calculating the volume of run-off generated it was two-dimensionally routed using the Wallingford procedure, a non-linear reservoir routing model.

The surface and subsurface elements are coupled at the nodes. The nodes are features such as manholes which convey surface flows to the sub-surface. Each node has an associated inlet capacity that limits the flow of runoff from the surface to the sub-surface.

The fully distributed hydraulic model was verified with the use of rainfall and flow data collected by a local monitoring system operated from 2010 till 2015. This network was made up of three tipping bucket rain gauges, a depth sensor for the Roding River outfall, and two depth sensors within the sewers. Further details on the monitoring system can be found within Pina et al. (2016).

4.2.1 Initial Conditions

The initial conditions specify the simulated hydrological conditions within the model with regards to the water levels, flows, and velocities of surface water at the beginning of the simulation. For the Cranbrook Catchment the initial conditions primarily defined the lake depths and baseflows within the drainage network. Additionally, the initial soil wetness was defined; this affected the rainfall runoff characteristics of the catchment. The initial soil wetness was identified through the use of regional maps which define soil wetness for catchments across the UK.

4.2.2 Effect of Precipitation Events on the Storm-water Flows of the Cranbrook

The model described in the previous section was used to investigate the effect that potential precipitation events may have on the flow regime of the catchment. To illustrate the effects that future precipitation events may have on the drainage system four nodes in the catchment were chosen. These four points were chosen as they were located along the trunk sewer and they were spread out from the upper reaches of the catchment to the catchment outlet. In doing so, it is possible to see how the flow regime changes through out the drainage system; thereby showing how rainfall-runoff response in different regions of the catchment. The hydrographs of flow through the nodes was extracted from the Infoworks ICM model. The nodes and their associated flows are shown in Figures 4.3 through 4.6.

The nodes are shown in order of their location in the catchment, with A representing the flows from the uppermost regions of the catchment to D which represents the catchment outlet. These four nodes were used for illustrative purposes to explore how rainfall response changes across the catchment. For each node a hydrograph is shown; within each of the hydrographs the effect of the standard 30 year return period rainfall event can be seen along with the 30 year return period event modified to concentrate the precipitation into a shorter time period, and the 30 year return period with a 50% increase in depth applied.The choice of 30 year return period storm was chosen based upon British Standard EN 752:2008 British Standard Insitute (2013) and is expanded upon in Chapter 5. The storm with concentrated precipitation is denoted as being "highly peaked", the degree to which this storm was concentrated is discussed in Chapter 5. The 50% increase was chosen as it represented the upper realm of potential futures explored; this choice of upper limit is discussed in detail in Chapter 5. In brief, these upper limits were felt to offer a sufficiently broad exploration of futures and exploring beyond these limits was not worth the added computational expense or analytical investment. The rainfall events are shown in Figure 5.5

Across all four nodes several common trends are identified. The peak flows resulting from the standard thirty year return period storm and the highly peaked storm are similar in magnitude. However, the storm of standard peakedness resulted in a more immediate storm-water response but the response is more gradual than those that occur from highly peaked storms.

The storm with a 50% increase in precipitation depth caused the most rapid flow response and the largest peak flows out all three storms explored. Unlike the other storms, the storm with an increases in rainfall depth did not exhibit a rapid reduction in flows upon the peak rainfall passing. As the flows through the nodes are explored, flow rates increase as one progresses from the upper regions of the catchment to the catchment outlet. However, there is a slight decrease in peak flow between the nodes above and below the storage lake, displaying the lake's ability to attenuate flow. Flow regimes in the lower regions of the catchment do not display a decrease in flows in the second half of the storm events. Storm water flows remain relatively constant towards the end of the simulated storm events due to the delayed arrival of storm water from the farthest regions of the catchment reaching the catchment outlet.

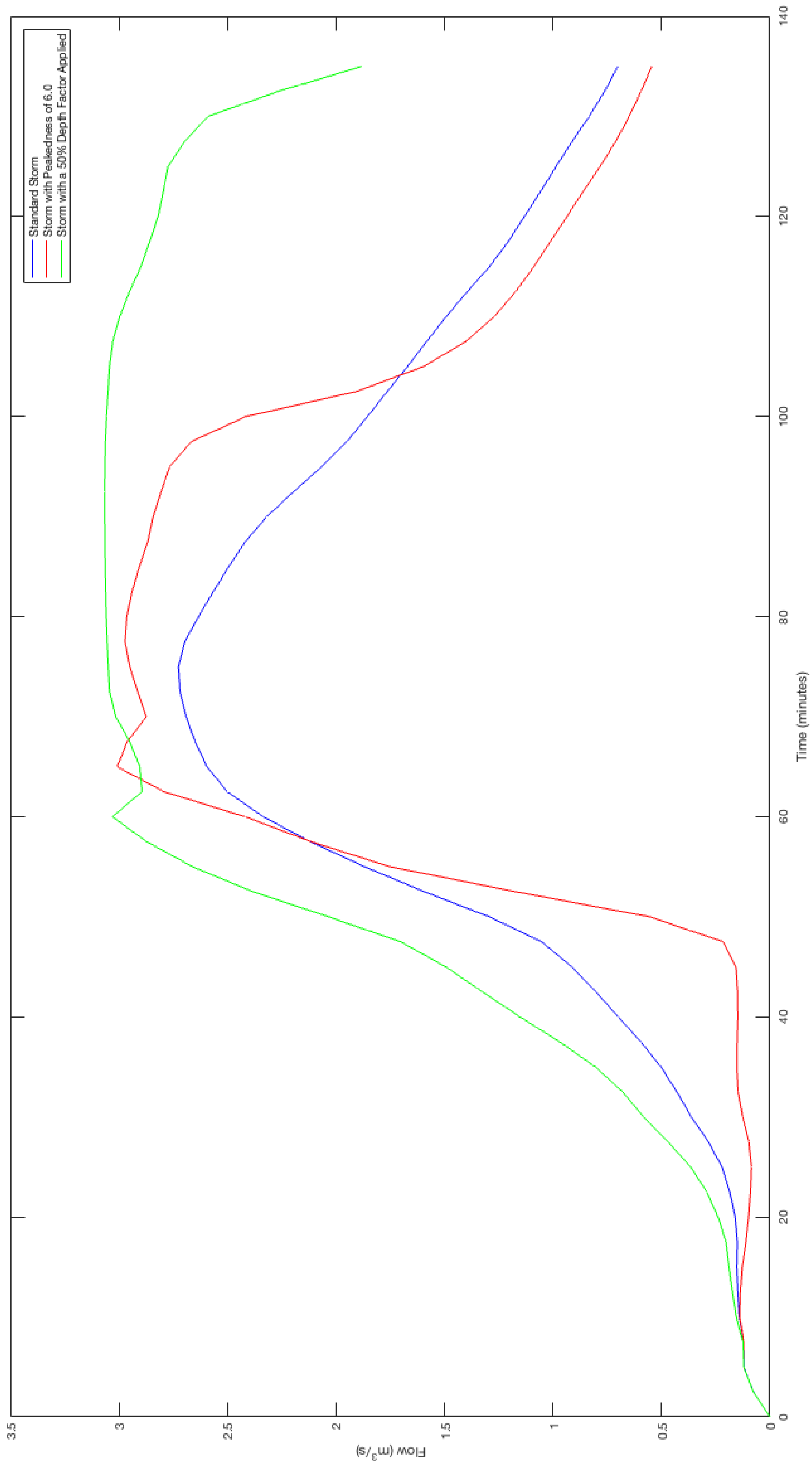


Figure 4.3: Hydrograph at node A, in response to three potential storms

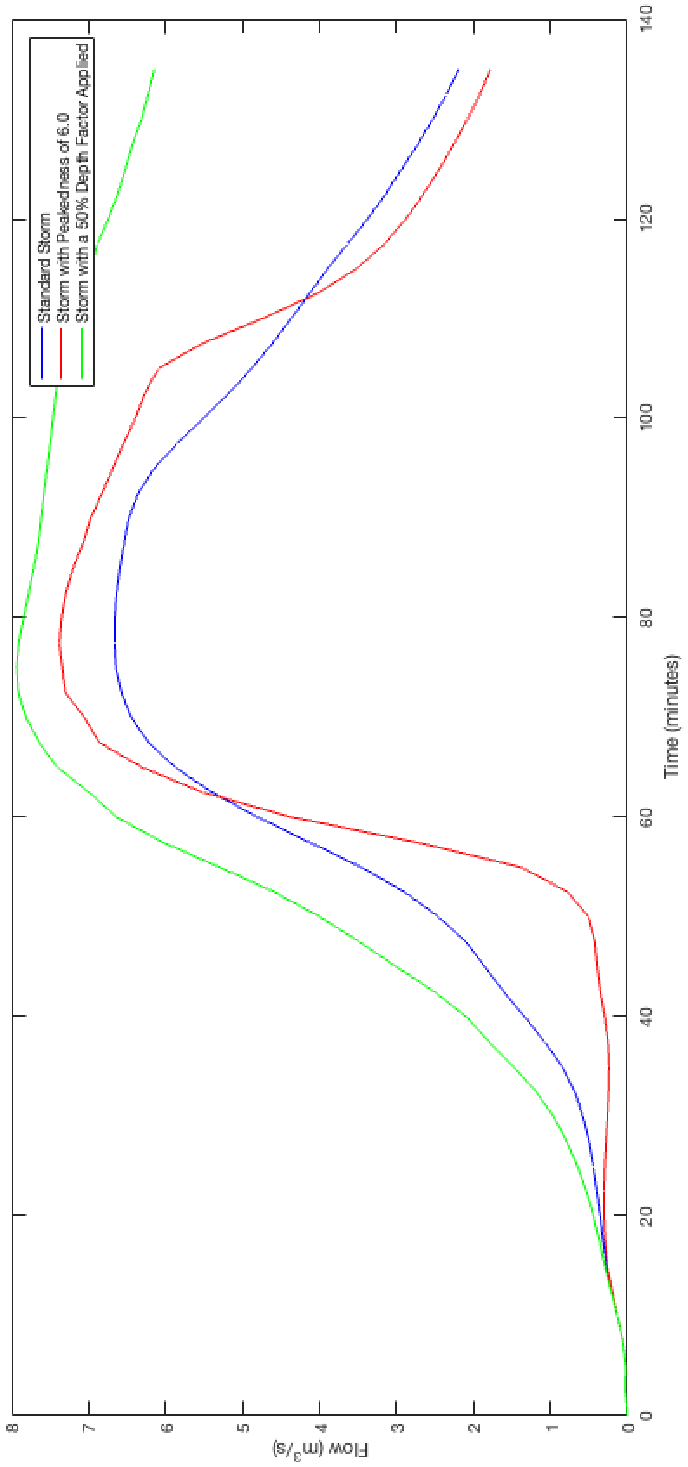


Figure 4.4: Hydrograph at node B, in response to three potential storms

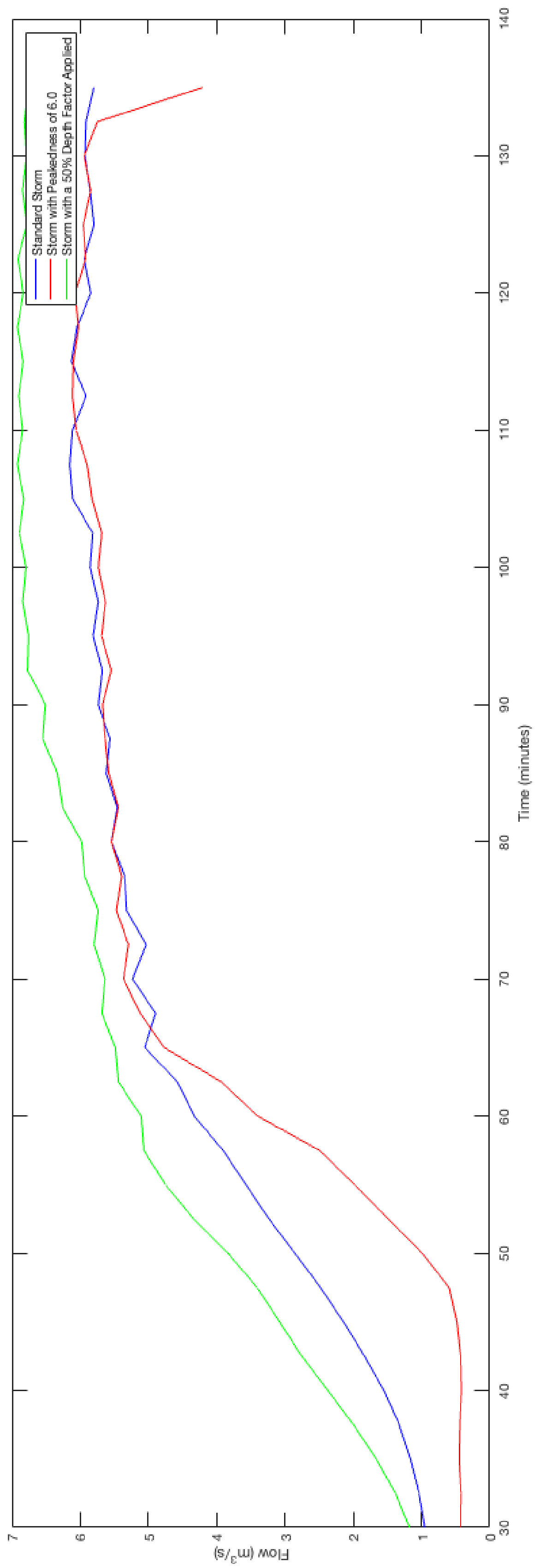


Figure 4.5: Hydrograph at node C, in response to three potential storms

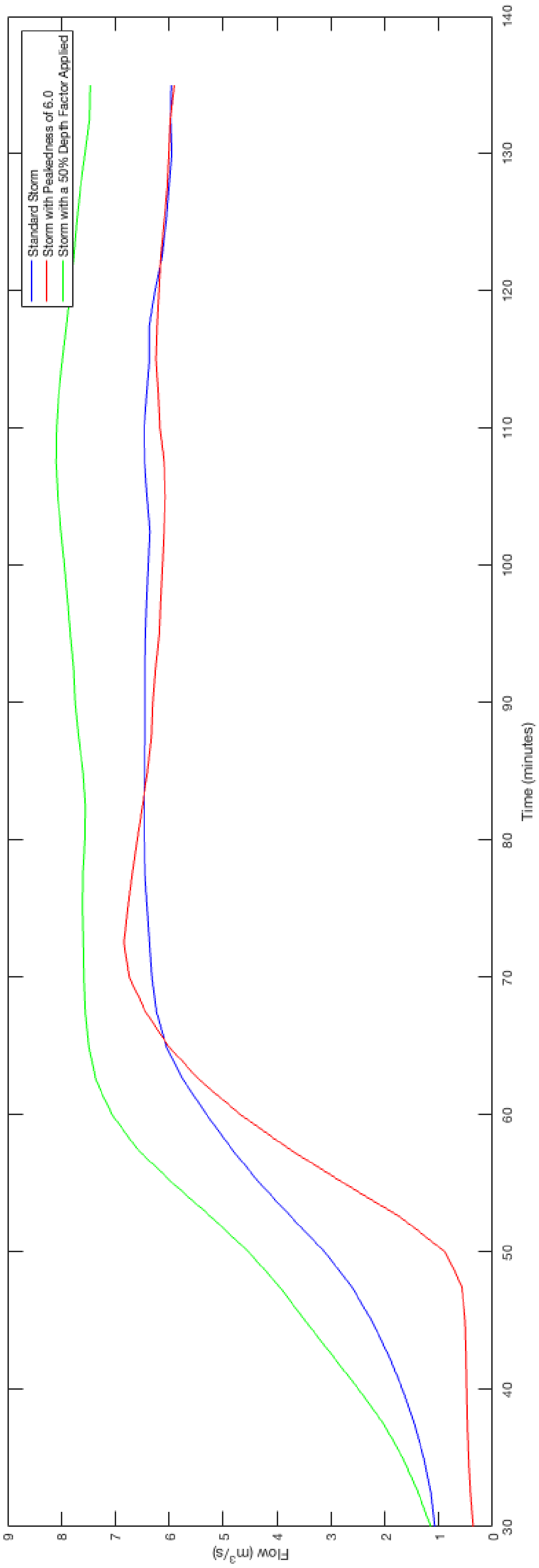


Figure 4.6: Hydrograph at node D, in response to three potential storms

4.2.3 Comparison of Model Results to the updated Flood Map for Surface Water

The Infoworks model utilised was calibrated and validated on a three year long data set of precipitation events and the associated flows in the drainage system as part of the RainGain project. This time series did not contain any storm events which would be considered extreme events. Due to this, there were concerns that the Infoworks model would be unable to replicate the surface water flood extent generated by a rare storm event. Any divergence between model results and reality would likely be amplified once the potential effects of climate change were simulated.

In order to assess the Infoworks model's ability to replicate real life flood extent it was compared against another flood model: the updated Flood Map for Surface Water (uFMSW). The updated Flood Map for Surface Water, created by the Environment Agency, is the output of a JFlow+ 2D hydraulic model for the entire UK (Environment Agency, 2013). The model was created with the intention of providing the public with a basic understanding of the flood risks within their local area. As the uFMSW was used to model the entire of the UK it contains several assumptions which negate its utility as a model for urban flooding. Primarily, the uFMSW does not explicitly model the effects of drainage infrastructure. Instead, the model assumes a uniform drainage removal rate of 12mm/hr regardless of the drainage infrastructure in place. Additionally, the model uses a relatively coarse spatial resolution of $2m$ by $2m$ which fails to capture many of the details present within the urban environment. These two features greatly impede the uFMSW's use as an urban flood modelling tool.

The maximum surface flood water extent for a 30 year return period storm for the Cranbrook were extracted from the uFMSW and Infoworks models. The extents were compared against one another and a 55% agreement in flood extent coverage was found. Based upon similar comparisons made in the past this is a relatively good level agreement of the two extents given the simplifications present within the JFlow hydraulic model. The uFMSW's underestimation of flooding is consistent with with previous comparisons that have been made between the uFMSW, empirical observations, and other flood models which more accurately reflect the physical processes of a given catchment (Environment Agency, 2013).

4.3 Conclusions

This chapter delineated the modelling framework used to simulate the rainfall runoff characteristics of the Cranbrook Catchment. It is shown that the flood extent generated by the Infoworks offers a good level of agreement with other flood models. This chapter also delineates how the Cranbrook responds to storms with various changes factors applied. These rainfall responses underpin how the catchment will respond to potential adaptations being implemented. In forthcoming chapters the results of this modelling framework were used to assess the efficacy of potential adaptation strategies, provided the basis for generating Adaptation Pathways, and provided information on the flood risk reduction benefits of potential adaptations.

Chapter 5

Generation of Adaptation Pathways

5.1 Introduction

London's population has grown significantly over the past 25 years with continued growth expected in the decades to come (Mayor of London, 2016). The currencomparisonofhydrographs.pngt drainage system, originally built over 150 years ago, has served London well. However, London's urban drainage system, similar to many other cities, is currently operating in a vastly different hydrological environment compared to its original design conditions. Increases in the amount of impermeable land have directly lead to increased volumes of runoff to be conveyed by the sewer system resulting in large pressures on the drainage system. Independently of land use, climate change has augmented the storm flows that need to be conveyed in order to maintain the current standard of protection.

To maintain the required level of pluvial flood protection as defined by law existing drainage systems must be adapted. However, there is a high degree of uncertainty surrounding future land use and climate conditions (Hallegatte, 2009). As highlighted in the Literature Review, the resulting condition of deep uncertainty obfuscates whether design choices will remain valid in the future (Hallegatte et al., 2012).

As noted in Chapter 2, situations of deep uncertainty are characterised by an inability to accurately assess the probability of an event occurring. This ambiguity may extend to both the the direction and magnitude of change (Regos, 2012). The lack of credible projections results in the notion that there are multiple valid paths to the future which must be entertained (Hallegatte et al., 2012). The resulting ambiguity poses serious problems for decision makers, specifically with regards to choosing appropriate models, identifying and characterising sources of uncertainty, and ranking potential policies (Kwakkel et al., 2014). Traditionally, these shortcomings are overcome by increased data collection-however, under conditions of deep uncertainty this may not lead to improved predictive ability as the past is of limited use as an indicator of the future (Milly et al., 2008).

In the context of urban flooding deep uncertainty arises through the interactions of multiple sources of uncertainty such as population growth, land use change and climate change (Babovic et al., 2018; Deng et al., 2013).

Given the limited degree of confidence that can be attributed to predictions about the future it is critical that methodologies of planning that account for these uncertainties are explored and utilised. Traditional methods of planning infrastructure, based off deterministic projections are inappropriate given the magnitude of the uncertainties being facing by planners (Groves and Lempert, 2007).

In order to assess the present and future risks of urban pluvial flooding an Adaptation Tipping Points approach was utilised. The ATP method was chosen as it focuses on incremental change a necessity for urban drainage adaptation; it is easily explainable to a broad range of stakeholders; and has the ability to be easily integrated into other planning frameworks such as antifragility or DAPP.

This work represents the first known investigation of how a drainage system responds and can be adapted to a combination of risk aggravators. The risk aggrevators explored in this work are increases in a design storm's total depth and increases in the storm's ratio of peak to mean rainfall intensity. The study is also unique with regards to large number of potential adaptation strategies investigated and analysis of the simplifications for the long term urban drainage planning. The Cranbrook's current drainage system was stress-tested against 121 potential storms; 53 potential adaptation strategies were then modelled and stress-tested against the same 121 potential storms. The results of the 6534 model runs were then utilised to generate a set of Adaptation Pathways on how to adapt the drainage system to potential changes in the design storm. Based upon these pathways practical recommendations are laid out with regards to which short-term solutions allow for further adaptation and how decision-making can be structured to cope with these uncertainties. This chapter is based on the paper Babovic & Mijic (Under Review) in the Journal of Flood Risk Management.

5.2 Cranbrook Catchment

As noted in Chapter 4, the analysis and modelling conducted in this study is based upon the Cranbrook catchment. The Cranbrook is located within the North East of London in the Borough of Redbridge as shown in Figure 5.1. The catchment has a drainage area of approximately 9 km^2 and is predominately urban with the exception of a large park that contains two offline-lakes.

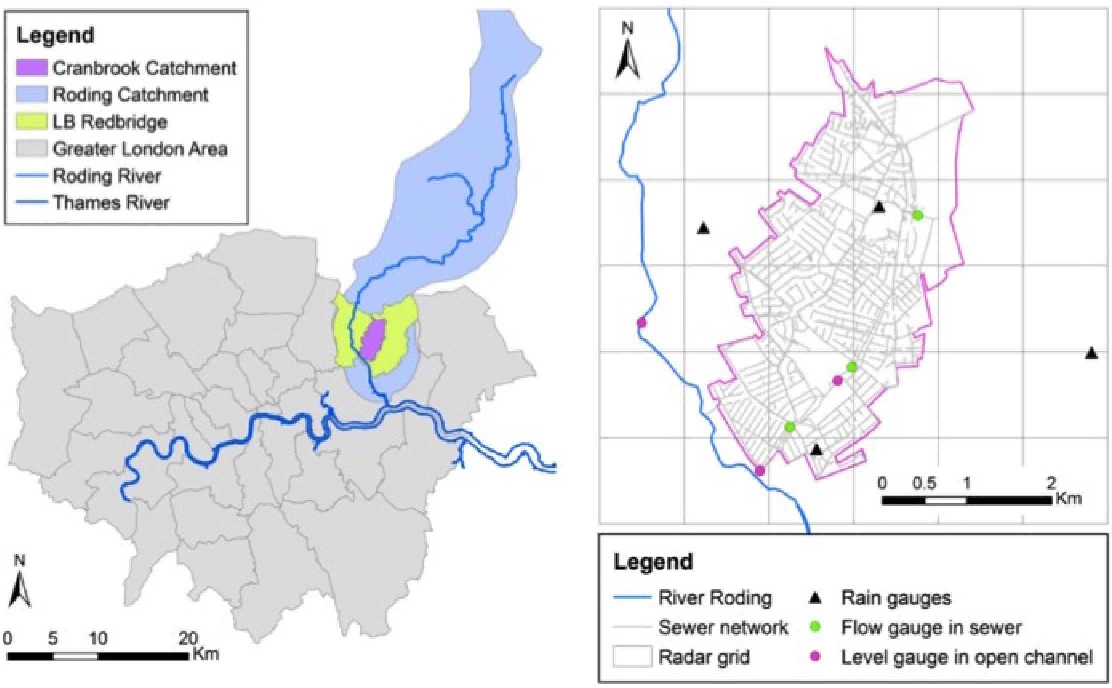


Figure 5.1: Map of the Cranbrook Catchment (Simões et al., 2015)

The main watercourse running through the catchment is 5.75 km long, of which 5.7 km is culverted and have become part of the mainly separate drainage system. The drainage system discharges into a tributary of the River Thames.

The catchment has a population of approximately 41,000 inhabitants resulting in a population density of 4,500 people per km^2. The Cranbrook catchment is situated in a borough, that is projected to experience a 15% increase in population by the year 2040. These projections are likely to be an underestimate of true population growth which is expected to be exacerbated by the construction of a new rail-commuting corridor. It is highly probable that this population growth will result in an increased pace of urban creep.

Being highly urbanised, the Cranbrook catchment is characterised by a rapid response to rainfall. Surface run-off resulting from heavy rainfall generally flows and ponds along the natural drainage pathways, most of which have been covered by impervious surfaces. Partly due to this, the Cranbrook catchment has experienced flooding in the past, with events reported as early as 1926. There have been at least two major flood events since the turn of the century in addition to these major events there have been a number of smaller surface water floods (London Borough of Redbridge, 2011).

5.2.1 British Drainage Regulations

The Cranbrook's drainage system must conform to British Standard EN 752:2008, the United Kingdom's national regulatory framework that lays out the requirements for drainage systems and sewer systems for urban areas. The standard requires that the frequency of surcharge of manholes within urban areas must be limited to once in every thirty years (British Standard Insitute, 2013).

Beyond national legislation, within the London region there is a complex tapestry of governmental bodies that produce recommendations and guidance on how to manage flood risk. These include the Mayor's Office, the Local Authority, and the Environment Agency. Together, these agencies have produced at least twenty sets of guidance that influence how London's flood risk should be managed.

5.2.2 Climate Change

There has been evidence to suggest that climate change has already begun to affect the precipitation patterns within the United Kingdom (Jenkins et al., 2009b). However, there is a high degree of heterogeneity in the direction and magnitude of change across the UK. Broadly speaking rainfall depths have decreased in the summer and the South-East of Britain; whereas concurrently rainfall depths have increased in the winter and North of Britain (Jenkins et al., 2009b). These trends are illustrated in Figure 5.2.

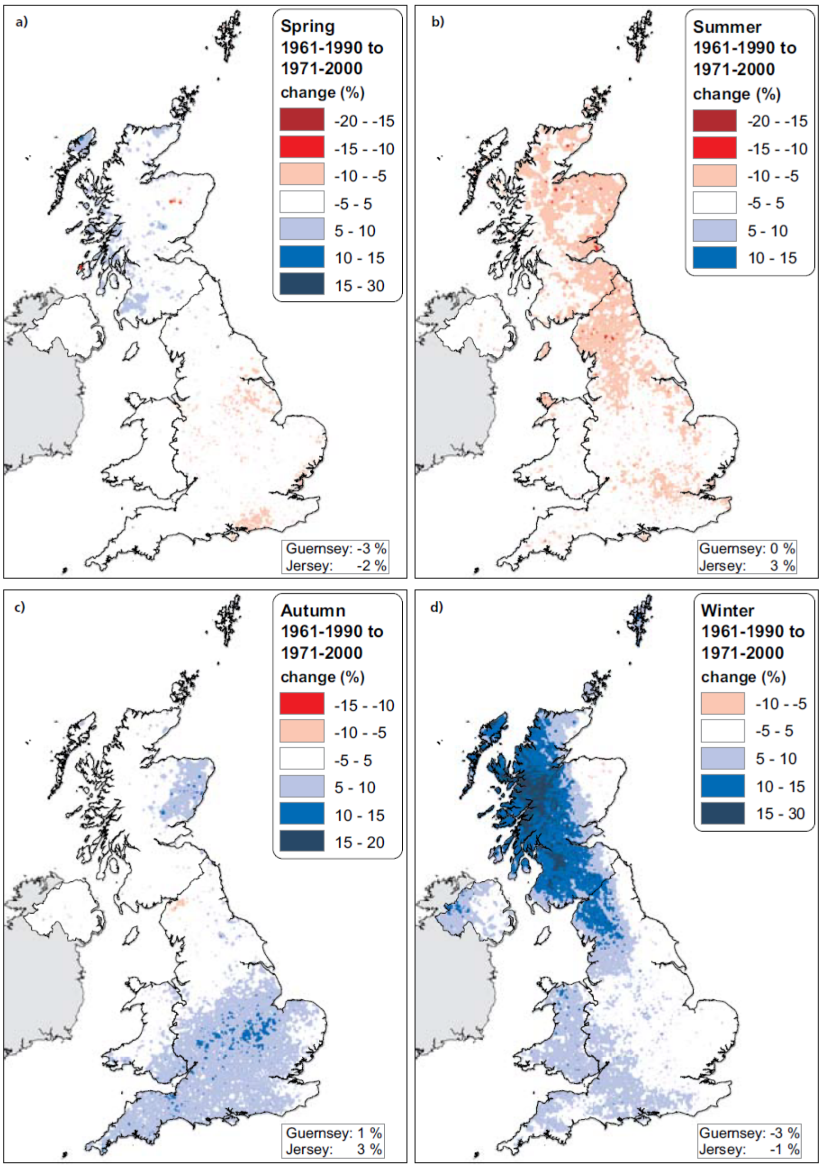


Figure 5.2: Percentage change in total average precipitation amount between 1961-1990 and 1971-2000 for a) spring, b) summer, c) autumn and d) winter; (Jenkins et al., 2009b)

In addition to this, it should be recognised that the effects of climate change on precipitation vary across temporal scales. For example, there is evidence to suggest that while aggregate precipitation depths will decrease in the summer, the precipitation that does occur will be concentrated in fewer and stronger summer showers (Kendon et al., 2014). A great deal of investigation has been performed on projecting precipitation change at temporally coarse resolutions of one month or longer. However, drainage design is ideally conducted utilising sub-daily precipitation information. Sub-daily and sub-hourly precipitation change is a domain of climate change research where projections and data are scarce, However, there are indications that individual rainfall events will increase in intensity although it is not clear to which degree these changes will occur (Chan et al., 2014).

5.3 Adaptation Tipping Points Methodology

Adaptation Tipping Points (ATP) is a methodology of adaptation planning in which a system is modelled and then exposed to increasingly large stresses in order to identify when the system will no longer be able to operate to a desired level of reliability (Kwadijk et al., 2010). These levels of operation are typically defined through the use of national standards; however, any chosen reliability criterion could be used to conduct this analysis. Adaptation Pathways builds upon Adaptation Tipping Points by modelling a system adaptation once the reliability metric is breached. The ATP methodology is then repeated on the adapted system, resulting in a series of Adaptation Pathways that can deliver a minimum level of system reliability across a planning horizon.

The methodology to conduct an ATP analysis is as follows (Kwadijk et al., 2010):

1. A driver of change is chosen and the current management strategy to manage that driver identified.

2. The acceptable standards for system performance are defined. This is achieved through regulations or stakeholder consultation.

3. The driver of change is modified and the stress acting on the system increased until the failure condition is exhibited. This allows for the identification of which potential future conditions lead to acceptable flood standards being compromised.

3a. The conditions under which an ATP will occur may be transformed into an estimate of when they may occur through the use of projections.

4. If desired, repeat Steps 3 and 4 for the proposed adaptations, this will result in a number of adaptive strategies.

The ATP method exposes systemic vulnerabilities for which potential adaptation measures can be identified. This is known as an effect-based method as the focus is on the performance of the system under potential change as opposed to developing and utilising projections (Gersonius et al., 2012). The benefit of the ATP method is that the analysis is independent of climate change scenarios; climate change scenarios can be used to create a timeline of when ATPs may be reached. However, due to the presence of deep uncertainty these projections are likely to be erroneous. The ATP method allows for decisions to be made despite these uncertainties as the choice and exploration of potential futures is independent of forecasts (Babovic et al., Accepted). The Adaptation Tipping Points approach allows for the implementation of low-regret adaptation as it addresses the most urgent effects of climate change while structuring solutions with path-dependence in mind such that they are viable elements of potential future adaptation strategies.

5.4 Development of Adaptation Pathways

The Adaptation Tipping Points methodology as outlined in Section 5.3 and Figure 5.3 was modified and applied to the case study in this paper through the following procedure.

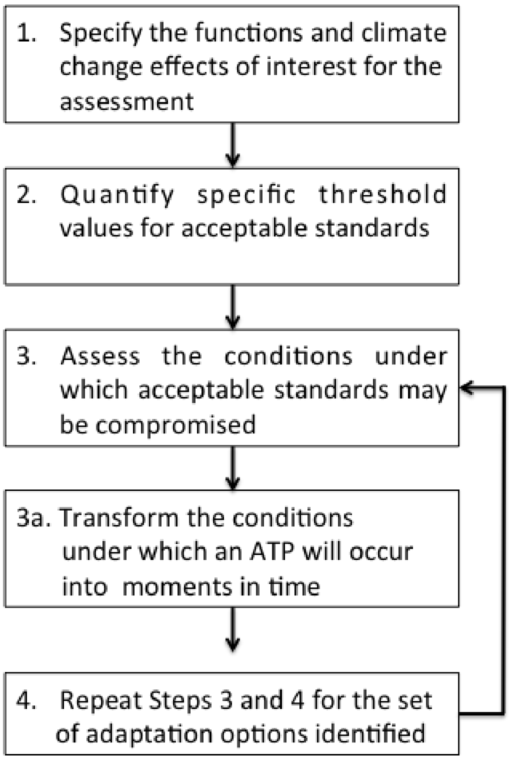


Figure 5.3: Adaptation Tipping Points Methodology, adapted from Gersonius et al. (2012)

Step 1: Identification of drivers of change

The drivers of change investigated were potential increases in the rainfall depth and increases in the peakedness of the design storm. Peakedness, defined as the ratio of peak rainfall intensity to mean rainfall intensity describes the temporal distribution of precipitation across the duration of the storm. The current pluvial flood defence infrastructure in Cranbrook is made up of a network of drains, gullies, and culverts.

Step 2: Identification of reliability criterion

The reliability standards for pluvial flood defence are defined within the British Standards and are such that the frequency of manholes surcharging should not exceed a thirty-year return period.

Step 3: Assessing the system's adaptation tipping point

The 'current' design storm-the thirty year return period storm with no climate change factors applied-was generated following guidance from Part Four of the Flood Estimation Handbook (Houghton-Carr, 1999). The resulting storm profile is shown in Figure 5.4.

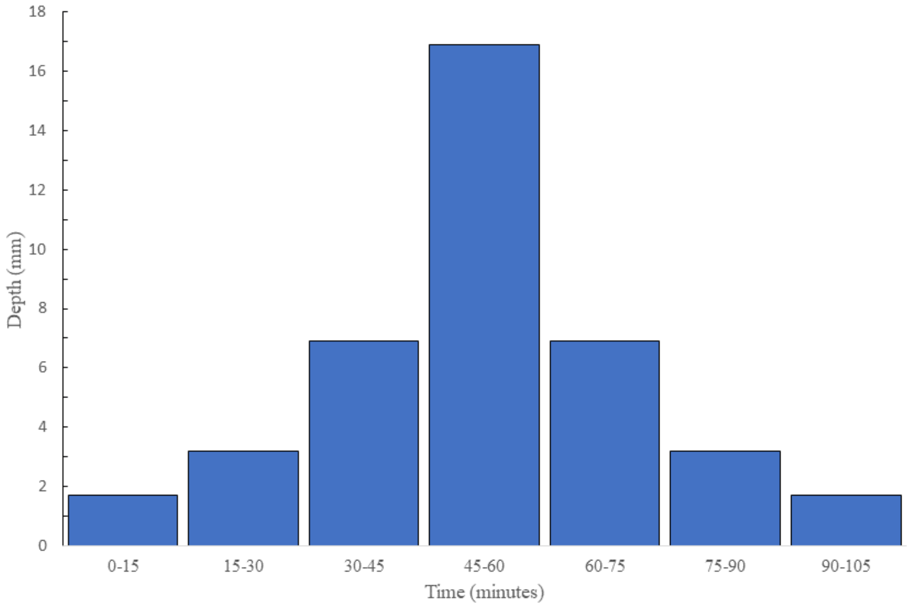


Figure 5.4: Standard Hydrograph for a 30 year return period storm for the Cranbrook Catchment

A variety of flood models can be utilised to simulate the effects of potential precipitation events. Four models were tested which incorporated a range of simplifications of physical processes; as a result there was a wide range of model run times. The models and the associated run times for one simulation are shown in Table 5.1.

Table 5.1: Models Tested and their Associated Run Times

Model	**Run Time**
1D-1D Simplified	1.5 Seconds
1D-1D	40 Seconds
1D-2D Semi-Distributed	2.5 Minutes
1D-2D Fully-Distributed	5 Minutes

These models were originally created and calibrated as part of the RainGain Project (Simões et al., 2015; Ochoa-Rodriguez et al., 2015). Based upon these run times and the degree to which physical processes were replicated, the catchment was modelled using a 1D-2D fully distributed

Infoworks ICM 6.5 model. The model's structure and properties were discussed in Chapter 4.

Upon establishing a design storm and an appropriate flood model the design storm was modified such that the potential effects of climate change on storm properties could be explored.

The design storm depth was modified by applying climate change factors at 5% intervals; ranging from a 0% to 50% increase in depth, resulting in 11 potential increases in depths. Additionally the temporal distribution of precipitation was modified. Following guidance from the Flood Estimation Handbook (Houghton-Carr, 1999), urban drainage systems are designed using a summer storm. This resulted in a symmetrical storm with a ratio of peak to mean intensity, known as peakedness, of approximately 3.0. The peakedness is dictated through two shape parameters: alpha and beta. These parameters were modified in such a way as to generate storms that had peakednesses in the range of 3.0 to 6.0 at increments of 0.3. Modifying the peakedness has the effect of increasing the peak intensity while keeping rainfall depth constant. The effects of increases in depth and peakedness can be seen in Figure 5.5 which plots the current design storm, the design storm modified to have a peakedness of 6.0, and the design storm with a 50% increase in depth. This range and increment was felt to sufficiently cover the space of potential futures while balancing computational cost.

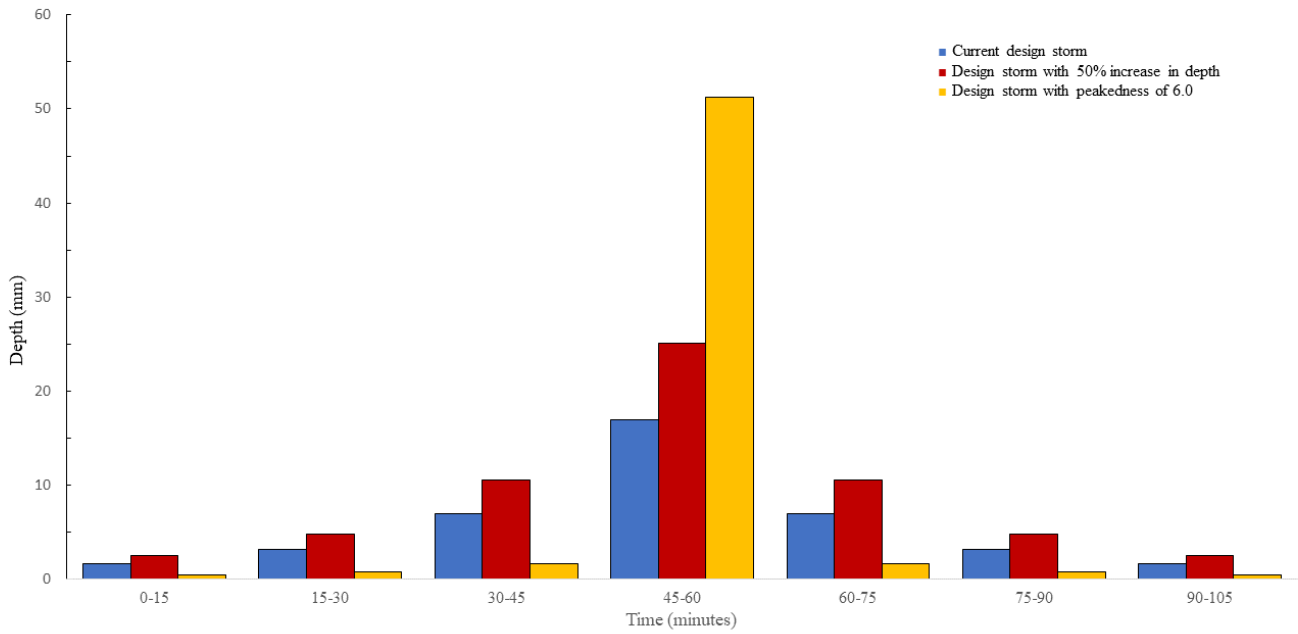


Figure 5.5: The effect of different climate change factors on the thirty year design storm

The 11 depth increases and 11 storm profiles resulted in a total of 121 potential future rainfall scenarios that could be examined. These were simulated within Infoworks ICM to identify under which combination of increases in depth and peakedness the system would fail to offer sufficient protection to a thirty-year return period storm.

Step 3a: Conversion of ATPs to forecasts

In order to convert the Adaptation Tipping Points to an estimate of when the tipping points may occur, projections on how individual storm events may change are needed. Projections of how individual rainfall events' depths may change due to climate change have been generated by the Environment Agency (2016). These data were utilised to derive continuous projections for event level precipitation increases as shown in Figure 5.6. Three potential projections are shown which represent the 90%, 50%, and 10% probability levels-denoted as high, central, and low scenarios.

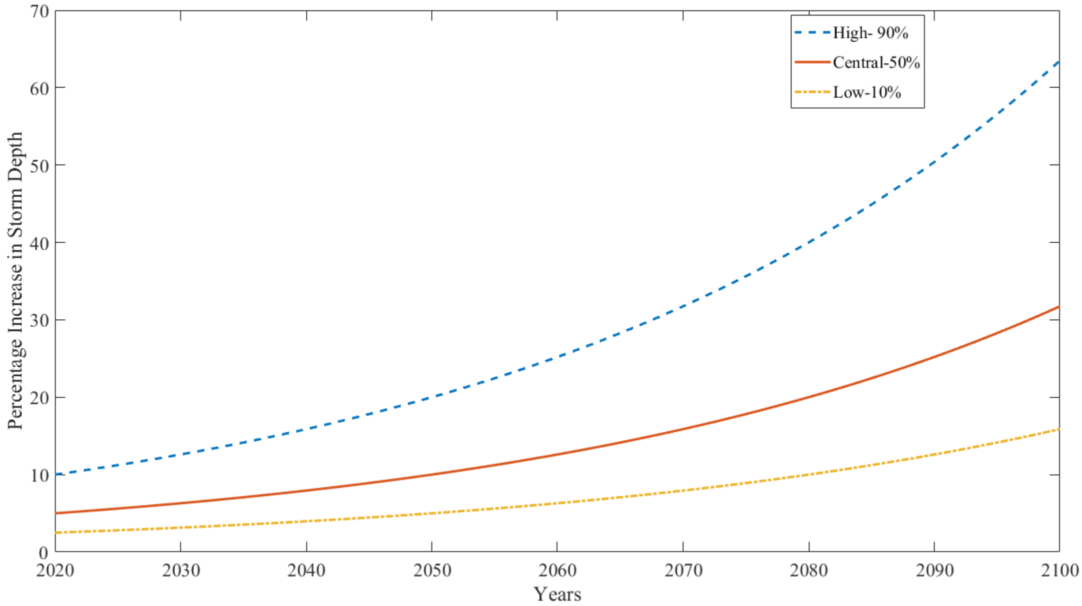


Figure 5.6: Projections for increases in the precipitation depth of rare storm events, author's own based on data from Environment Agency (2016). The high, central, and low labels refer to the 90%, 50%, and 10% probability estimates respectively.

Step 4: Identification of Adaptation Options

In the UK, a range of planning documents provide guidance on pluvial flood solutions that are being actively considered and applied by local government. These documents recommend various options to improve the drainage system in the Cranbrook catchment and provide potential adaptations to ATPs being reached. The options were identified after consulting the documents laid out in Table 5.2. The subset of options that were chosen to be investigated included

Table 5.2: Planning documents consulted to identify potential drainage adaptations for the Cranbrook Catchment

Agency	**Document**
Borough of Redbridge	Strategic Flood Risk Assesment (London Borough of Redbridge, 2016) Local Development Framework (London Borough of Redbridge, 2008) Local Flood Risk Management Strategy (London Borough of Redbridge, 2015) Surface Water Management Plan (London Borough of Redbridge, 2011)
Mayor's Office	Sustainable Planning Guidelines- Sustainable Design and Construction (Greater London Authority, 2014b) London Plan (Mayor of London, 2016) Mayor's Water Strategy (Mayor of London, 2011) The Mayor's Climate Change Adaptation Strategy (Moss et al., 2012)
Environment Agency	Regional Flood Risk Appraisal (Greater London Authority, 2014a)
National Government	National Planning Policy Framework (Department for Communities and Local Government, 2012) Flood Risk (Great Britain, 2009) Flood and Water Management Act (Great Britain, 2010)

converting 25% of roofs to green roofs, converting 50% of roofs to green roofs, converting 20% of streets to porous pavements, converting 40% streets to porous pavement, deepening a large storage lake by 0.5m, deepening the lake by 1m and increasing the diameter of the trunk sewer by ten per cent. These choices of adaptation were primarily chosen based upon the Local Flood Risk Management Plan, the surface Water Management Plan, the Mayor's Water Strategy and The Mayor's Climate Change Adaptation Strategy. Once combinations of potential adaptations are considered the number of strategies increased from 7 to 53; the constituent solutions of each strategy are shown in Figure 5.7. Each strategy was tested against the storms derived previously to identify their behaviour in the face of potential changes in precipitation; resulting in a total of 6534 model runs. Costs were not considered at this point in the analysis,the focus of the study was on generating reliable Adaptation Pathways and identifying robust adaptation strategies first and foremost.

	Convert 25% of roofs to green roofs	Convert 50% of roofs to green roofs	Convert 20% of pavement to porous pavement	Convert 40% of pavement to porous pavement	Deepen the lake by 0.5m	Deepen the lake by 1m	Increase trunk drain diamater by 10%
Strategy 1	■						
Strategy 2		■					
Strategy 3			■				
Strategy 4	■		■				
Strategy 5		■	■				
Strategy 6				■			
Strategy 7	■			■			
Strategy 8		■		■			
Strategy 9					■		
Strategy 10	■				■		
Strategy 11		■			■		
Strategy 12			■		■		
Strategy 13				■	■		
Strategy 14	■		■		■		
Strategy 15		■	■		■		
Strategy 16	■			■	■		
Strategy 17		■		■	■		
Strategy 18						■	
Strategy 19	■					■	
Strategy 20		■				■	
Strategy 21			■			■	
Strategy 22				■		■	
Strategy 23	■		■			■	
Strategy 24		■	■			■	
Strategy 25	■			■		■	
Strategy 26		■		■		■	
Strategy 27							■
Strategy 28	■						■
Strategy 29		■					■
Strategy 30			■				■
Strategy 31	■		■				■
Strategy 32		■	■				■
Strategy 33				■			■
Strategy 34	■			■			■
Strategy 35		■		■			■
Strategy 36					■		■
Strategy 37	■				■		■
Strategy 38		■			■		■
Strategy 39			■		■		■
Strategy 40				■	■		■
Strategy 41	■		■		■		■
Strategy 42		■	■		■		■
Strategy 43	■			■	■		■
Strategy 44		■		■	■		■
Strategy 45						■	■
Strategy 46	■					■	■
Strategy 47		■				■	■
Strategy 48			■			■	■
Strategy 49				■		■	■
Strategy 50	■		■			■	■
Strategy 51		■	■			■	■
Strategy 52	■			■		■	■
Strategy 53		■		■		■	■

Figure 5.7: Breakdown of the adaptations that make up every strategy

5.5 ATP Modelling Procedure

In order to conduct the Adaptation Tipping Points methodology as displayed in Chapter 5, the procedures outlined in Figure 5.8 were conducted.

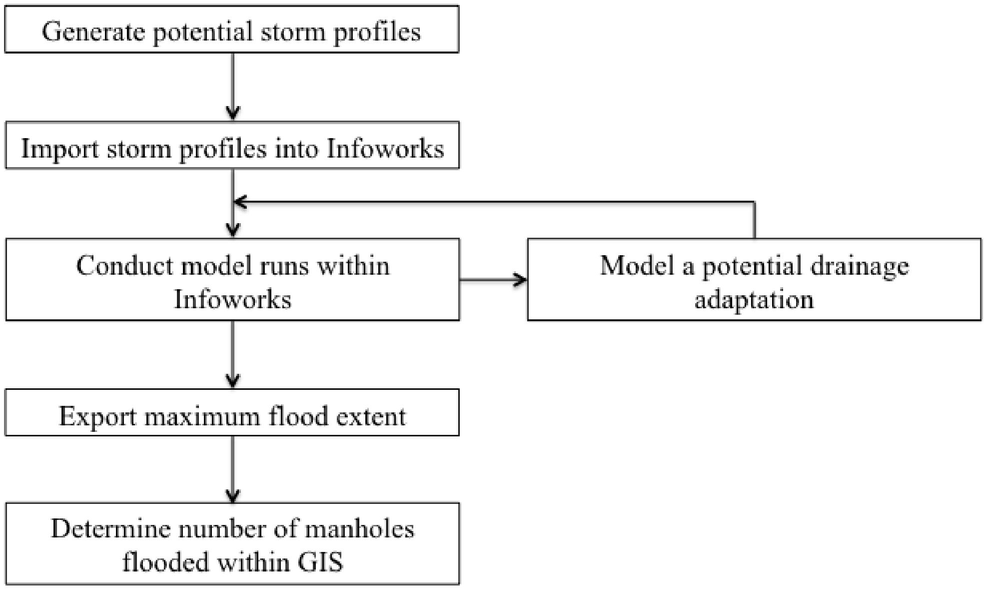


Figure 5.8: Flow chart of modelling procedure

The ATP procedure explored two potential changes to the thirty year return period design storm: increases in the total precipitation depth of the event and increases in the peak to mean intensity of the storm, termed peakedess.

Storms were imported into Infoworks as groups of eleven. Each group of storms exhibited the full range of peakednesses explored along with an associated increase in depth. For example, all of the storms from peakedness 3.0 to 6.0 that also had a 5% increase in storm depth applied were imported as one group. This procedure was conducted 11 times for all increases in depth explored. This resulted in an organisational hierarchy of storms with the top layer composed of 11 increases in depth; beneath each of these increases in depth were 11 storms of varying peakednesses.

Each adaptation strategy identified for investigation was modelled within Infoworks. As the primary focus of the study was the evaluation of the effectiveness of the adaptation strategies the individual strategies were used as the main organisational unit of organising model runs.

Beneath this layer were the flood simulations for a drainage strategy experiencing the imported storms.

The effectiveness of a given strategy was determined by its surface water flood extent. These extents were generated by simulating the effects of the storms on every drainage adaptation strategy. The simulations were run in the same groups of eleven that they were imported as. For each rainfall event the precipitation was assumed to fall uniformly across the entire area of the catchment.

Each strategy modified the original Infoworks land use model in order to reflect the potential drainage adaptation strategy being stress-tested. Green roofs were modeled by modifying the porosity of the polygons which define structures. Similarly, the porous pavement was modelled by modifying the porosity of the road surface element of the Infoworks model. The depth of the lake was altered by modifying its properties. These changes resulted in many new "versions" of the Cranbrook with each one corresponding to a different adaptation strategy.

In order to minimize the computational time to complete a simulation the time step was chosen to be five minutes. This is coarser than what is generally used for flood simulations, however this time-step was decided to be appropriate given the need for fast models within Decision Making under Deep Uncertainty modelling.

The duration of the simulation was chosen to be 135 minutes. The highly urbanised nature of the catchment and associated quick runoff response resulted in the maximum flood extent occurring slightly after the maximum precipitation intensity. As the goal of the hydrological modelling was to determine the maximum flood extent there was no need to simulate the catchment until the surface water had receded; this greatly reduced the computational expense of a single simulation as well.

In order to further reduce computational time the model was instructed to parallelise two-dimensional flow computations processes onto the desktop computer's Graphical Processing Unit (GPU). The use of the GPU was found to considerably reduce the computational time needed to complete a simulation. Based on a set of test runs there was an 80% reduction in the time needed to complete a simulation when a GPU was utilised to simulate the two-dimensional flow.

For every assessment of the manholes flooded conducted, the number of manholes flooded for that strategy, peakedness, and depth factor was noted. This resulted in a data set of the number of manholes flooded for any adaptation strategy investigated within the range of storms explored.

5.6 Results & Discussion

5.6.1 Modelling Results

The procedure for establishing how many manholes were flooded was repeated for all 53-adaptation strategies across the 121 potential future storms. This resulted in a data set that specified the number of manholes flooded for any combination of potential increase in design storm depth and peakedness for any adaptation strategy. When more than 2% of the manholes were surcharged the drainage system was considered to exhibit failure, signifying that the Adaptation Tipping Point had been reached. The 2% level was chosen as it offered a reasonable level of "head-room" for failure in extreme events while not allowing for excessive failure in such extreme events. A lower threshold was not chosen as there was always some level of localised failure somewhere in the system which would not have made economic sense to address. The Adaptation Maps in this chapter and Appendix 1 were created based upon this data set of flooded manholes and risk aggrevators.

Adaptation Pathways

As noted earlier, this study explored potential increase in depth by utilising increases in 5% increments. Under these 5% increments many strategies did not exhibit improved flood protection. To illustrate; if only increments of 5% are used the Cranbrook's current drainage system has an ATP equivalent to a 30% increase in depth. If 25% of roofs are converted to green roofs the drainage systems ATP remains at 30%. While drainage capacity was added to the Cranbrook's system, it was insufficient to raise the drainage system's ATP. This is due to the ATP of the adapted system still being lower than 35%.

To overcome this, the following methodology was implemented.

As noted earlier, the reliability criterion of the Cranbrook's drainage system is breached when 2% of manholes are flooded, which is equivalent to 154 manholes flooding. Under the original methodology the climate change factor that resulted in more than 154 manholes flooding was identified as the ATP. In order to more accurately identify an adaptation strategy's ATP the exact increase in depth that resulted in 154 manholes flooding was found. This was achieved by linearly interpolating between the number of manholes flooded for the climate change factor that resulted in more than 154 manholes flooding; and the number of manholes flooded for the climate change factor below it. For example, if 25% of roofs were converted to green roofs 159 manholes would be flooded for a design storm with a 30% increase in depth. When the same strategy was exposed to a storm with only a 25% increase in depth 140 manholes were flooded. By linearly interpolating between the numbers of manholes flooded the exact ATP was found to occur at an increase in depth equal to 29%.

When this analysis was repeated for all 53 strategies it was found that the majority of adaptation options resulted in a small increase in the drainage system's ATP, usually in the range of 2-3%. While this data post-processing is trivial to conduct, the interpolation masks the non-linear relationship between the increase in design storm depth and the number of manholes flooded. This non-linearity is likely to be a feature of both the modelled drainage system's response to extreme rainfall and the clustering of manholes, both of which result in small increases in spatial flood extent leading to relatively large increases in the number of manholes flooded. In future analyses a more refined exploration of the effects of increases in depth should be utilised; perhaps exploring increases in depth at the 2% or 2.5% increment.

The resulting data set of which increase in rainfall depth resulted in a strategy's ATP being reached was the basis upon which the Adaptation Pathways were generated. In order to generate the pathways the individual adaptation options were ranked by their ability to augment the capacity of the drainage system. In doing so, the adaptation strategies that had the highest ATP's were identified. Once relative performance is considered, certain adaptation strategies become untenable, for example two adaptations outperform three adaptations. By identifying which adaptations are untenable the number of strategies to be considered is greatly reduced. Once this has been completed; this resulted in an exercise to find a logical combination of adaptation strategies that linked individual adaptation options, which represent the simplest adaptations, to the adaptation strategies with the highest ATPs, which were composed of multiple adaptations implemented sequentially.

Pathways were developed in such a way that only one adaptation option should be implemented at a time. In instances where similar adaptation strategies had the same ATP, the simplest strategy would be chosen. For example if there was a choice on whether to choose between a one meter deepening of a lake and 25% green roofs; and a one meter deepening of the lake and 50% green roofs; and they had the same ATP, the simpler option would be chosen. This reflects the desire to keep capital and operational expenditures to a minimum.

Adaptation Pathways for Increases in Storm Depth

The Adaptation Pathways for storms with peakedness of 3.0 are displayed in Figure 5.9. Amongst all of the adaptation strategies considered the greatest possible increase in the drainage system's ATP was found to equal a 44% increase in depth. For such a high level of flood protection to be delivered a combination of solutions that addressed both infiltration issues and pipe network capacity were required. In this particular case this combination of adaptations was the conversion of 40% of pavement to porous pavement, 50% of roofs to green roofs and deepening the storage lake by one metre.

An analysis of individual options showed that augmenting the trunk sewer's capacity by increasing its diameter would result in a 2% increase in the drainage system's Adaptation Tipping Point. However, there were no logical paths from this option to adaptation strategies with higher Adaptation Tipping Points. This path therefore leads to lock-in and offers only a limited ability to improve the drainage system in the future; meaning that when this increase is

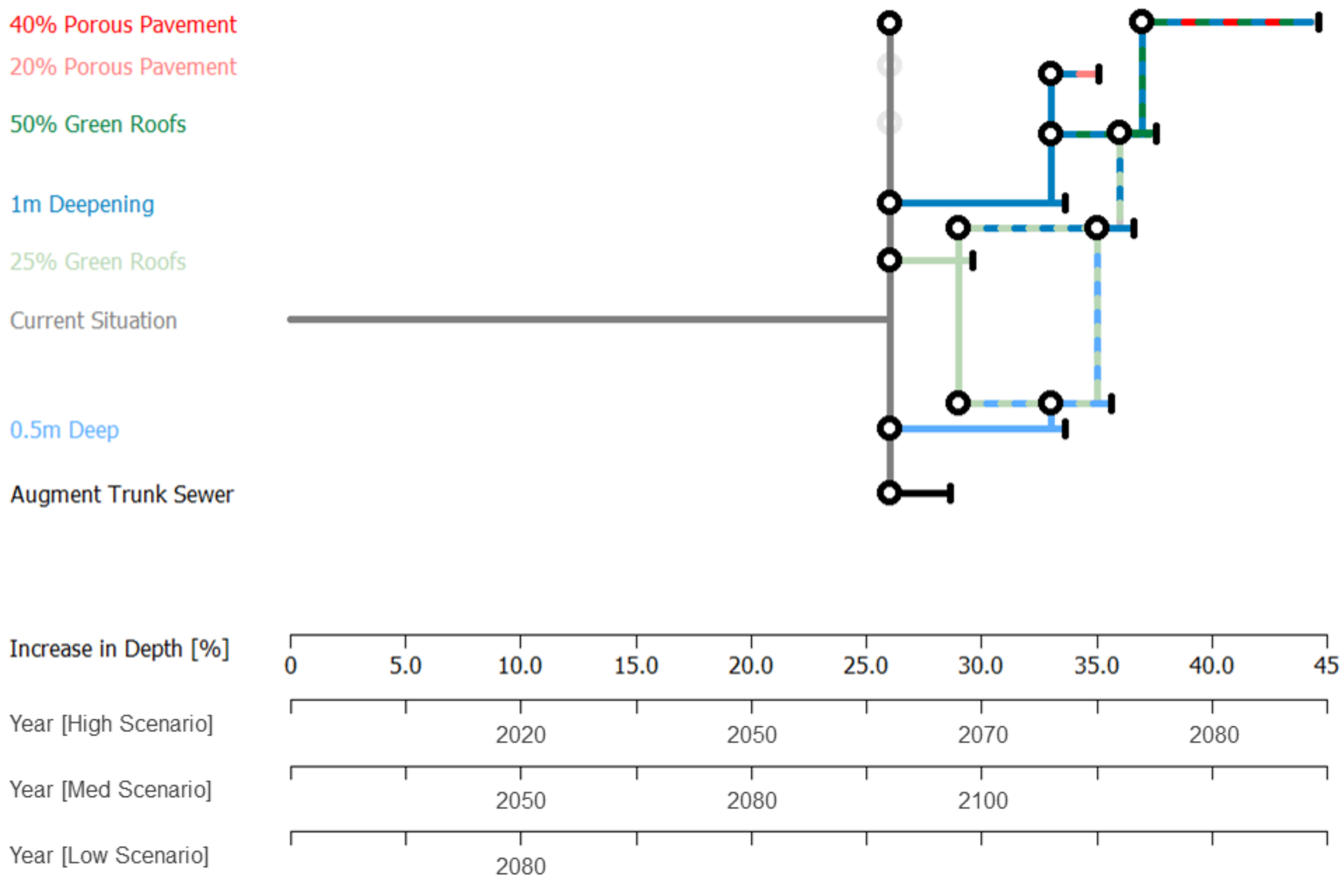


Figure 5.9: Adaptation Pathways for storms with increasing depth and peakedness of 3.0

used in conjunction with other adaptations those adaptations do not add drainage capacity. Both permutations of increasing the lake's retention volume were shown to have sizable impacts on the drainage system's capacity. Porous pavements are shown to be ineffective at adding drainage capacity as stand-alone adaptations. However, they are effective as adaptations once the drainage system's capacity has been increased by increasing lake depth.

Based upon the pathways in Figure 5.9, in order to develop an adaptation strategy that delivers the greatest drainage capacity in the short-term, local decision makers should choose to convert either a quarter of roofs to green roofs or to deepen the lake by one meter. These options offer logical progressions to more robust drainage strategies should they be needed. As the design storm's depth is increased, the array of solutions able to deliver such a high level of reliability converge to a combination of green roofs and lake deepening.

Based upon the pathways shown, it is hypothesized that there are two elements of pluvial flood protection that define the efficacy of a particular adaptation option. These are system capacity, defined as the amount of runoff able to be conveyed by the drainage system; and secondly, the rate at which runoff is infiltrated into porous surfaces.

The initial efficacy of increasing the size of the trunk sewer and the volume of the retention lakes, in comparison to the Sustainable Drainage systems (SuDs) options, would indicate that there is a lack of capacity within the current drainage system. Therefore, initially, surface flooding is due to pipes surcharging and a lack of conveyance capacity within the drainage system. The capacity provided by the lakes and augmented trunk sewer both address this lack of drainage capacity.

These two factors, system capacity and infiltration rate, also reflect why SuDs are better to be implemented as a second adaptation. After a lack of drainage capacity is addressed, the primary source of flooding is an inability to remove runoff from the surface. Therefore blue-green solutions which reduce surface runoff are more effective after the drainage capacity has been increased. These two factors also reflect why the total ATP of an adaptation strategy isn't simply the sum of the individual adaptation option's ATPs. Any adaptation will address one of these elements; the adaptation that most thoroughly addresses the weaker element of the drainage system would be the most effective adaptation.

Timing of Adaptations

Potential increases in depth were converted to estimates of when they may occur based upon the projections shown in Figure 5.6, this resulted in the three different timelines displayed below the x-axis in Figure 5.9. Depending on which scenario is used to convert the ATPs to a timeline there can be large differences in the timing of the implementation of the options. For example, the current drainage system's Adaptation Tipping Point could be reached in the year 2060, 2090, or beyond 2100 depending upon whether the high, medium or low scenario is used. This uncertainty may be reduced in the future through improved understanding of how climate change will affect individual storm events.

This high degree of variability in the potential timing of options suggests that local monitoring is needed in order to identify the rate at which precipitation depths for individual rainfall events are changing. Doing so will ensure that decision makers are aware of which timeline they are travelling along. Discerning a climate change signal for either depth or peakedness will prove to be a challenge however, due to the large variations between storms and the difficulty of separating the effects of increases in total precipitation depth and changes in the temporal distribution of precipitation.

Adaptation Pathways for Increases in Storm Peakedness

Increases in the peakedness of a storm reflect the effect of multiple possible processes that could increase flood risk. Peakedness' contribution to increased flood risk greatly depends on whether it is coupled with an associated increase in a storm's precipitation depth.

For storms with increases in depth of 10% or less the Infoworks model results show that flood risk was not affected by even extreme increases in peakedness. This indicates that the current system will offer sufficient protection from flooding if runoff volumes remain constant-even if they are more concentrated. This is likely to be the case if changing precipitation patterns move towards shorter and more intense storms.

Storms that had a 35% or higher increase in total depth resulted in flooding for almost all adaptation strategies, regardless of how peaked the storms were. This can also be observed in the pathways for increases in depth (Figure 5.9) where only a minority of strategies were able to prevent flooding for storms with high increases in depth but no increase in peakedness.

In between these two extremes there is a middle range within which there is heterogeneity in the efficacy of potential strategies. Therefore, peakedness only plays a role in the effectiveness of adaptation strategies if the design storm depth is also increased by 15-30%. Such an increase in runoff volume and concentration of runoff most accurately reflects the potential impact of land use change. Figure 5.10 displays the adaptation pathways for increases in peakedness for a fixed increase in rainfall depth of 15%.

There is a degree of choice in the possible adaptation options that can be utilised to adapt to

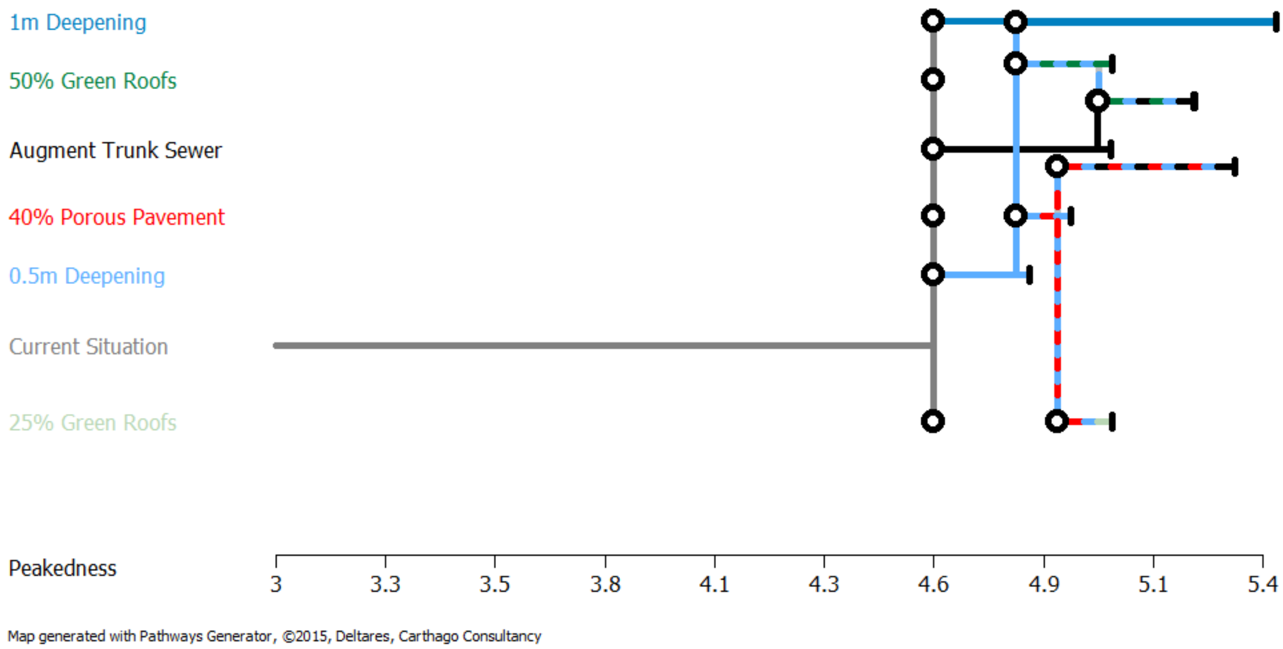


Figure 5.10: Adaptation Pathways for storms with increasing peakedness and depth increase of 15%

changes in peakedness. Unlike the pathways for only increases in depth, a reasonably high level of adaptation can be achieved by utilising a variety of pathways.

For example, increasing the lake's depth by one meter is the simplest adaptation that offers the greatest possible increase in the drainage system's Adaptation Tipping Point. Alternatively, increasing the lake's depth by half a meter would represent a more incremental adaptation that would open several potential pathways such as re-dredging the lake by another half a meter or by implementing porous pavements. Increasing the trunk drain's diameter would also be a viable adaptation and would allow for further adaptation in the future if the catchment's flood risk becomes increasingly severe.

There are no known projections of how peakedness can change in the future due to climate change. Studies of how intensity may change exist (Kendon et al., 2014), however these studies focus upon how the distribution of future precipitation may change. These studies have not been translated to potential changes in storm peakedness as defined within the Flood Estimation Handbook, this creates a barrier in implementing these findings within the design process. Other projections of changes in intensity have been created but none specifically related to changes in peak to mean rainfall. Due to this it is not possible to derive estimates of when these ATPs may be reached. This impedes planning by hampering decision-maker's ability to assess how likely potential changes are and how far in advance adaptation options need to be implemented.

Comparison of Adaptation Pathways for Peakedness and Depth

The adaptation pathways for increases in rainfall depth result in a relatively clear pathway on how to adapt the system well into the future due to the convergence of the pathways on a solution that utilises lake deepening and green roofs. In comparison, the pathways for increases in peakedness do not converge to a singular best solution and there is a greater degree of choice in which adaptation options to implement.

There is a range of differences and similarities between the two sets of adaptation options. Within the adaptation pathways for peakedness, increasing the diameter of the trunk drain does not result in lock-in and allows for the development of increasingly robust flood defences. This runs counter to the pathways for increases in depth (Figure 5.9) where long term solutions to address flood risk do not include augmenting sewer systems. Increasing the lake depth is effective at addressing both increases in depth and peakedness. This is especially true if the lake's depth were increased by one meter. Alternatively, porous pavements are not shown to be particularly effective at addressing the flooding challenges on their own, however, they are shown to be effective complements to other solutions. In particular they are effective at augmenting the drainage system's capacity after other adaptations have been put in place and as the effects of climate change become increasingly severe. Lastly, there is a great deal of variation with regards to when green roofs are most effective.

The difference in the adaptation pathways has profound effects on the management of urban storm water. Increases in the storm peakedness result in faster and flashier responses to precipitation; as such, it can be seen as a proxy for land use change and urban creep. Therefore, the solutions identified as being effective at dealing with peakedness are well suited to protecting against increased runoff from impermeable surfaces. Conversely, solutions that are effective against increases in depth simply increase the total runoff drainage capacity. However, the efficacy of a given solution depends upon the previous adaptations and how they affected the current-day drainage system.

5.6.2 Comparison to Predict–then-Act Method

In order to assess the advantages and disadvantages of an ATP analysis in comparison to standard planning methods; a predict-then-act analysis was conducted for the Cranbrook case study. In this case the lifespan of an adaptation to the drainage system was assumed to be 50 years. The projections for increases in precipitation displayed in Figure 5.6 show that in 50 years time there will be a 28% increase in precipitation depth for the design storm under the high scenario. Based on this, the design storm was modified to reflect this increase in depth and simulated within the Infoworks ICM model described earlier. A design storm with this climate change factor applied, results in the reliability criterion being breached. Under such conditions, the enlarging of the trunk sewer would be the simplest solutions to addressing the gap in flood protection. Such a predict-then-act analysis requires only a minor computational expense; the run time for this model was approximately 7 minutes long. However, the predict-then-act method is based upon a high level of confidence in the prediction. The distribution of the rainfall projections is such that there is a ”long tail” towards large increases in storm depths. If the projection used underestimates the increase in depth by a small margin the system could exhibit significant flooding.

Within an ATP framework antecedent adaptations are chosen to act as a route to subsequent developments. The choice of an adaptation is made in such a way so as to avoid lock-in which results in a reduction of future choices. The predict-then-act method has a well-defined end date and little thought is given to longer term planning for even more intense rainfall. Upon comparing the solution suggested by predict-then-act against the full set of Adaptation Pathways in Figure 5.9 it is immediately evident that increasing the size of the trunk sewer is not identified as a suitable adaptation. This is as the modification of the sewer results in a lock-in and does not lend itself to be a common element of adaptation strategies that deliver high levels of protection. This stark difference shows how the broader exploration of futures in an ATP analysis prioritises solutions which can act as components of a larger adaptation strategy.

5.6.3 Comparison to Previous Work

Gersonius et al. (2012) applied the ATP methodology to an urban storm water management system in a neighbourhood in the Netherlands. The storm water system in Dordrecht was composed of three drainage subsystems; the effect of climate change on all three of these systems was investigated, however the minor system is most analogous to the Cranbrook's drainage system. Their ATP analysis was conducted with the use of a 1D-2D SOBEK-Rural model and a two-year return period design storm. The Adaptation Tipping Points for the different subsystems were converted to a timeline using data from the Dutch Meteorological Institute.

The drainage system was found to perform unacceptably when the rainfall depth was increased by 25%; under the worst-case climate change scenario this was projected to be reached in the year 2055. When compared to the Cranbrook, the current drainage system experiences its ATP at a 26% increase in depth. For the Cranbrook this ATP is expected to be reached in 2063 at the earliest. This implies that decision makers in the Netherlands have less time to develop their adaptation plans than their British colleagues although this difference in timing is highly influenced by the different climate models used. Gersonius et al. (2012) adapted the minor drainage system by disconnecting the roofs of public buildings and diverting the flows from paved areas to the open water system. This adaptation was found to perform acceptably up to a 45% increase in rainfall depth which was estimated to occur around 2100 at the earliest. This reflects the results of the adaptation pathways generated for the Cranbrook, which indicate that reliability can be ensured for up to a 44% increase in depth, projected to occur in 2085 under the high climate change scenario.

The work presented in this thesis builds upon this previous work in a number of ways. The modelling methodology uses a fully-distributed as opposed to semi-distributed methodologies. The size of the Cranbrook is several orders of magnitude larger than the case study in Dordrecht.

The number of drivers investigated and the number of strategies explored greatly increased the complexity of the study and provided a much deeper level of analysis with regards to potential solutions that maybe considered.

5.6.4 Discussion

A major assumption of the study is that the local council has sufficient funds to implement and maintain the Adaptation Pathways proposed. The economic cost and benefits of these solutions are critical in decision-making but have not been addressed within this chapter. The economic analysis of these pathways is conducted in Chapter 6 of this thesis.

The Flood Estimation Handbook methodology utilised to derive the design storms assumes that the temporal distribution of precipitation across a design event is symmetrical such as what is displayed in Figure 5.4. In reality, rainfall events do not exhibit these properties. A design storm that replicates physical storm behaviour would more accurately reflect real-world risk. Furthermore, the design storm assumes that the rainfall incident upon the catchment is spatially uniform; this is likely to be a minor issue given the case study's size. However, if this study's methodology were applied on a larger case study it may be of interest to utilise spatially heterogeneous precipitation in order to investigate how this affects the performance of the system.

The effects of land use change could be more explicitly investigated. The Cranbrook catchment is likely to experience development and urban creep, this will result in an increase in impermeable areas and will affect the runoff characteristics of the catchment. Increasing storm peakedness replicated some of this change. However, the explicit addition and exploration of land use change would result in a more through exploration of the space of future possibilities and improve the ability to plan and mitigate against potential increases in pluvial flood risk. However, this would aggravate an already highly computationally expensive analysis.

Many of the potential improvements to the analysis such as reducing the time step, increasing the spatial resolution, increasing the number of strategies to be evaluated, or increasing the number of potential risks to be investigated will increase computational loads. Individually, each model run requires a relatively short amount of time to complete, however, when aggregated across the different strategies and potential futures to be explored the resulting computational time can take many days or weeks. The Infoworks ICM model utilised was run on a desktop computer using an Intel Xeon E5 CPU with 16 GB RAM and a NVIDIA Quadro k620 GPU. The 6534 simulations run required the computer to run twenty-four hours a day for several weeks. This computational expense is likely to be a large impediment to future studies that attempt to marry DMDU and urban drainage. The computational time could be reduced in a number of ways. Firstly, more computationally efficient models could be developed. Alternatively, existing software could be used to run simpler, less physically based models. This follows the advice from Haasnoot et al. (2013) to utilise "simple but fast" models. Alternatively, the sampling rate from which futures are explored could be reduced. The aforementioned solutions result in a reduction in the fidelity of the analysis by utilising less physically based models or by exploring fewer potential futures. An especially powerful improvement to future DMDU analysis for urban drainage would be to leverage the power of cloud and high performance computing. Current iterations of Infoworks ICM and other flood modelling software have made progress towards utilising parallel computing and graphical-processing units. If this software could be migrated to perform on high-performance computers or the cloud it would be possible to run a thorough DMDU analysis without increasing run time or reducing the degree to which physical processes are replicated within the models.

The use of Adaptation Tipping Points also provides information about how a system can respond to potential events. Thereby delivering information about the stress-response relationship which is critical to developing antifragility of water systems.

5.7 Conclusions

The use of Adaptation Tipping Points and Adaptation Pathways allows for the development of an incremental and evolutionary strategy to adapt urban drainage systems to potential change.

This is achieved by identifying a sequence of short-term solutions that act as elements of long-term strategies. The use of Adaptation Pathways also effectively communicates the limits of various adaptations that can be implemented and the variety of pathways that exist. However, the assessment regarding the relative merits of any of these options is lacking. An economic assessment of the potential pathways would better inform decision makers on the costs and benefits of potential adaptations.

Two sets of Adaptation Pathways were generated, each for a different aspect of the design storm. These two elements of change were treated independently, however, it is likely that changes to the thirty-year return period event storm will involve changes to both peakedness and depth. Unfortunately there is no clear methodology in which to clearly display the effect of both of these factors of change in the context of adaptation pathways while also assuming that theses two variables are independent of one another. The Adaptation Pathways for all combinations of depth and peakedness are displayed in Appendix A of this thesis. The practical usage of the pathways is further constrained by the ambiguity surrounding the forecasts of potential changes and the resulting ambiguity surrounding when ATPs may be reached. This uncertainty is best managed by monitoring precipitation trends within the analysed catchment. This will provide decision makers with an indication of the rate at which Adaptation Tipping Points are being approached and provide information on how far in advance decision makers should begin to consider implementing an adaptation.

Looking forwards there is much to investigate with regard to the trade-off that exists between model accuracy and computational speed. Decision Making under Deep Uncertainty methodologies generally call for the use of simple and fast models. However there is much to investigate with regards to the trade-off between quick models and models which more fully capture the dynamics of the urban hydrological environment. While this question has always existed within the hydrological modelling community the problem is amplified by that fact that even a simple DMDU analysis involves dozens if not hundreds of model runs. Beyond questions of modelling significant opportunities exist to leverage the advances in high speed computing in order to reduce the time needed to perform such an analysis.

Chapter 6

Economic Evaluation of Adaptation Pathways for an Urban Drainage System

6.1 Introduction

As Decision Making under Deep Uncertainty methodologies have become more widely utilised there has been a growth in the use and generation of Adaptation Pathways. These pathways are meant to convey to policy makers how short term adaptations can acts as elements of longer-term adaptation strategies. However, these pathways do not convey the various pathway's relative costs and benefits. To address this problem in relation to urban pluvial flooding an economic analysis of a set of Adaptation Pathways was conducted. The results of the analysis were then compared against a standard economic analysis. This highlighted the pathways approach's ability to address uncertainty during the planning process. Furthermore, it was found that the order within which options are implemented can greatly affect the financial performance of an adaptation pathway even if the final combination of options is identical. This chapter is based on the journal paper Babovic et al. (Accepted).

Across the globe cities are implementing climate change adaptation strategies. These strategies aim to defend communities from the potential risks of climate change in relation to multiple factors including increased heat stress (IPCC, 2007), sea-level rise (IPCC, 2008), and flood risk (Jenkins et al., 2009a). The development of these adaptation strategies is hampered by the presence of multiple interacting uncertainties; these obfuscate future conditions and the degree to which infrastructure systems need to be adapted.

The aforementioned situation in which multiple poorly characterized uncertainties are present has been defined as "deep uncertainty". Under conditions of deep uncertainty traditional decision-making paradigms are inappropriate and Decision Making under Deep Uncertainty (DMDU) techniques should be utilised (Walker et al., 2013). These techniques utilise exploratory modelling to define the space of future possibilities and examine how potential strategies will perform within these hypothetical futures.

The presence of deep uncertainty is felt across many sectors such as energy generation (Bryant and Lempert, 2010), water supply (Zhang and Babovic, 2009), coastal flood risk (Reeder and Ranger, 2011), and transport planning (Kwakkel et al., 2010). Deep Uncertainty is also present within the problem of urban pluvial flooding (Babovic and Mijic, 2018). However, the deep uncertainties present within urban pluvial flooding have not been as widely explored as in the aforementioned fields. The development of urban drainage solutions to address the growing risk of urban pluvial flooding is hindered by the considerable uncertainties present in projections of future precipitation patterns and land use change.

The result of many DMDU analyses has been the generation of a set of Adaptation Pathways. These pathways are intended to structure policy makers' decision making in a technically realistic and logical manner. The intent of these pathways is to deliver sufficient information to decision makers such that they are then free to debate the relative merits and demerits of the presented solutions. However, the pathways alone generally contain limited information on the different pathway's costs and benefits.

The presented analysis undertakes a cost-benefit analysis undertaken on a set of adaptation pathways generated by Babovic et al (Under Review) for an urban drainage system, in order to deliver improved decision-making information. To date there has been only one known economic analysis of a set of adaptation pathways (Manocha and Babovic, 2017). Additioanlly, Woodward et al., (2014a) conducted an economic analysis on set of potential adaptations. The presented work builds upon previous work by using a more physically based assessment of flood damages and ecosystem services; as well as exploring a wider range of flood defence solutions over a wider range of futures.

The cost-benefit analysis was conducted by modifying the discounted cash flow (DCF) methodology to be applicable to Adaptation Pathways. It is hypothesised that performing a DCF analysis on Adaptation Pathways will deliver improved decision making for sustainable urban water management. The scope of the DCF was set such that the benefits of the pathways explored were defined as the sum of the ecosystem services and flood protection benefits. The costs of the options reflect both capital and operational expenditure.

6.2 Adaptation Pathways

The Adaptation Pathways upon which the economic analysis was conducted were generated in response to a need to develop a strategy to adapt the urban drainage system of the Cranbrook Catchment in the North East of London. The catchment has a 9km^2 drainage area. The primary land use in the catchment is suburban housing; as such the land surface is mostly impervious with the exception of a large park. The purpose of the study was to investigate how the catchment's pluvial flood risk characteristics would change with regards to potential changes in the thirty-year return period design storm. This was achieved by modifying the total depth of the design storm using climate change factors and by modifying the temporal distribution of precipitation across the duration of the storm. Eleven potential changes in depth were considered at 5% intervals, along with eleven potential changes in the temporal distribution of precipitation; this resulted in 121 potential precipitation events.

The current drainage system and catchment were modeled within Infoworks ICM as a fully distributed 1D-2D model. The 121 potential futures storms were then simulated against the current drainage system; this allowed for the identification of which combination of increases in depth and peakedness results in the current drainage system exhibiting failure. The increase in depth or peakedness that results in system failure is known as an Adaptation Tipping Point.

Upon reaching an ATP a potential adaptation was modeled within the flood simulation model. Various possible adaptations were considered in order to increase the drainage system's capacity. The options were identified after consulting a dozen sets of national, metropolitan, and borough guidance on developing increased drainage capacity. After consulting these documents seven potential adaptations were identified. Once combinations of potential adaptations were considered the number of strategies increased from seven to fifty-three.

Each of these fifty-three strategies was stress-tested against the 121 potential storms described earlier in order to identify their behavior in the face of potential changes to the design storm event. This resulted in a dataset of the number of manholes flooded for any explored increase in depth and peakedness. Figure 6.1 displays the Adaptation Pathways for increases in depth.

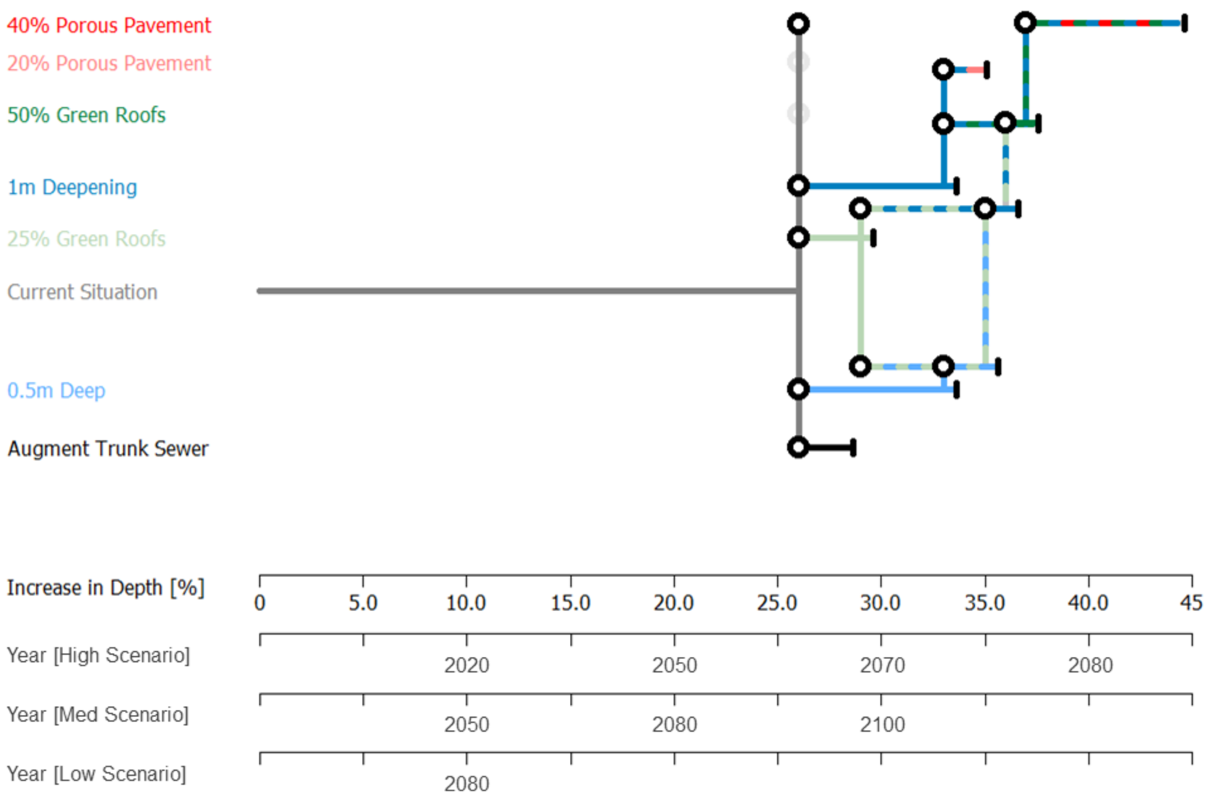


Figure 6.1: Pathways for increases in depth and no increase in peakedness

6.2.1 Timing of Potential Adaptations

Potential increases in rainfall depth were converted to estimates of when they may occur based upon projections from the Environment Agency (2016), shown in Figure 6.2. This resulted in three vastly different timelines of when Adaptation Tipping Points may occur. These timelines can be seen at the base of Figure 6.1. The high, medium and low scenarios represent the projections at the ninetieth, fiftieth, and tenth percentiles. There are no known projections of how peakedness may change due to climate change; due to this it was not possible to derive estimates of when these ATPs may be reached.

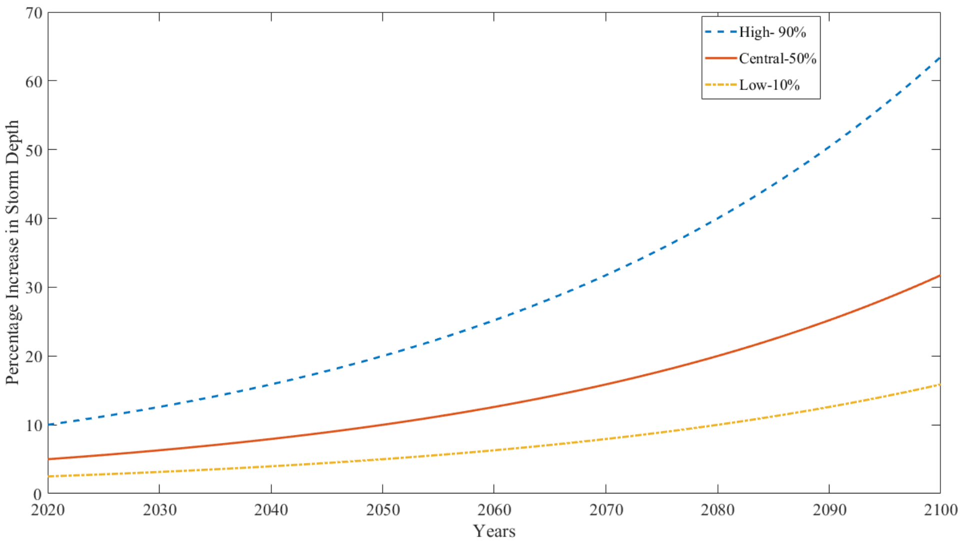


Figure 6.2: Potential increase in the precipitation depth of rare storm events over time, based upon Environment Agency (2016)

The ambiguity in when Adaptation Tipping Points may be reached raises serious questions with regards to the economic assessment of potential adaptation strategies. These questions have significant knock-on effects on the Net Present Value of the adaptation strategies.

6.3 Cost-Benefit Analysis of Pathways

Adaptation Pathways are intended to inform decision makers on which adaptation options should be implemented and the order within which they should be implemented. However, unless accompanied by additional metrics these pathways do not deliver a great deal of information with regards to the relative cost and benefits of the strategies. To address this, the total lifetime costs and benefits of the various paths through Figure 6.1 were evaluated. The benefits were assumed to be the sum of the flood risk and ecosystem benefits of the pathways. The costs of the proposed adaptation strategies encompassed both the capital and operational expenditures of the options.

By economically analysing a set of Adaptation Pathways after they have been generated it is possible to have a high degree of confidence in their ability to deliver reliable service. We therefore avoid the risk that reliability has been compromised by other metrics such as financial performance.

The Adaptation Pathways for increases in design storm depth were chosen to be analysed; this is due to the availability of projections for how the design storm depth's will increase over time. The presence of projections allowed for the lifespan of a potential adaptation to be determined. This information is critical as it allows for the creation a timeline of when adaptations may be needed and when they may expire.

One of the great benefits of Adaptation Pathways is that decision makers have an element of choice between different solutions, all of which can achieve the same objective. Due to this element of choice, all potential paths to the future had to be economically assessed. The potential paths within Figure 6.1 were identified, resulting in the 18 potential paths that are displayed in Figure 6.3.

The paths are defined by the combination of options and order in which they are implemented. This can result in situations where certain combinations of solutions having multiple paths associate with them. Multiple paths for the same final combination of adaptations are due to the same solutions being implemented in differing sequences. These paths were the unit of analysis upon which the economic assessment was performed. The paths and the order in which their component adaptations were implemented can be seen in Table 6.1.

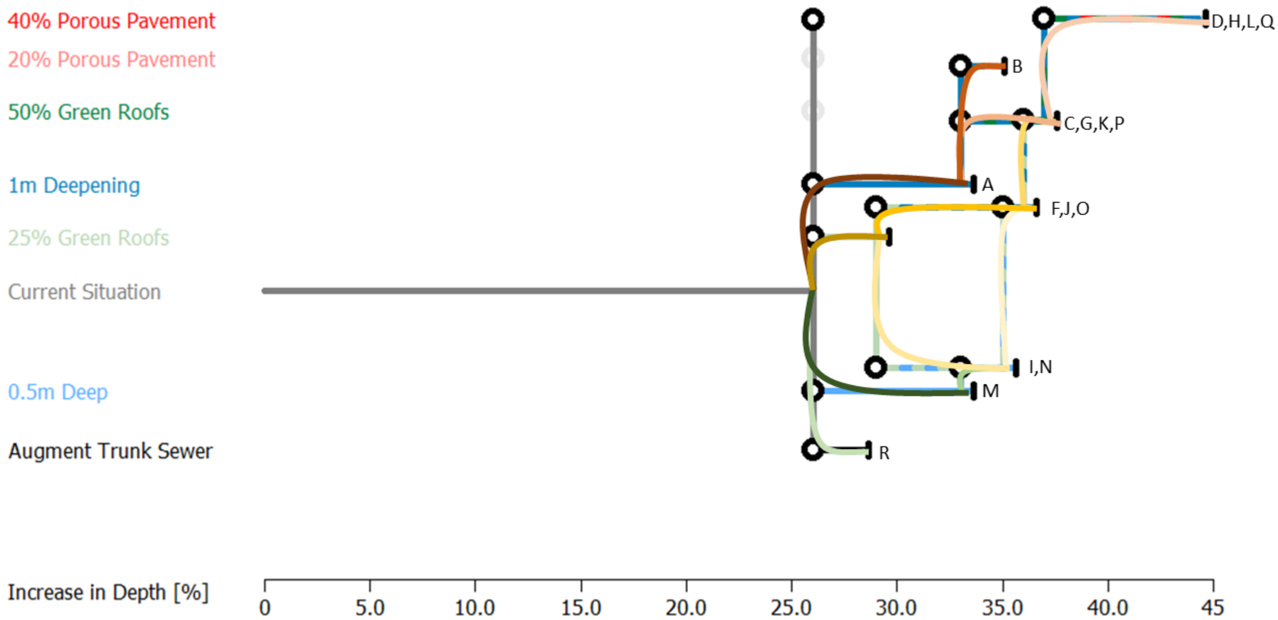


Figure 6.3: Potential Paths Through the Adaptation Tube Map, colours represent individual paths which all have unique sequences of adaptations

6.3.1 Flood Protection Benefits

For every path, the percentage increase in storm rainfall depth that resulted in an adaptation being implemented and that adaptation's ATP were noted. This defined the range of increase in depth within which the flood risk reduction benefits would be reaped.

The economic benefit of a flood risk reduction measure is equal to the value of the damage that was avoided by implementing the measure. Several methodologies exist to calculate the economic damage of a simulated flood; these can include market prices, inferential methods, expressed preference, and benefit transfer methods (Penning-Rowsell et al., 2013).

In order to assess the economic damage from flooding the data and methodology of the Multi Coloured Manual (MCM) (Penning-Rowsell et al., 2013) was used. The MCM uses a benefit-transfer method of flood damage estimation such that historic flood information is used to identify the relationship between flood depth, flood extent, and economic flood damage.

This study only assessed the direct property damage incurred by a storm. The Cranbrook catchment is made up of 4468 buildings; each of these structures was assigned a MCM land use category, such as commercial property or a detached dwelling. Each MCM land use category

Table 6.1: Paths and the order in which their component adaptations are implemented

Path	Order of Adaptations
A	1m Lake Deepening
B	1m Lake Deepening & 20% Porous Pavements
C	1m Lake Deepening & 50% Green Roofs
D	1m Lake Deepening & 50% Gren Roofs & 40% Porous Pavements
E	25% Green Roofs
F	25% Green Roofs & 1m Lake Deepening
G	25% Green Roofs & 1m Lake Deepening & 25% Green Roofs
H	25% Green Roofs & 1m Lake Deepening & 25% Green Roofs & 40% Porous Pavements
I	25% Green Roofs & 0.5m Lake Deepening
J	25% Green Roofs & 0.5m Lake Deepening & 0.5m Lake Deepening
K	25% Green Roofs & 0.5m Lake Deepening & 0.5m Lake Deepening & 25% Green Roof
L	25% Green Roofs & 0.5m Lake Deepening & 0.5m Lake Deepening & 25% Green Roof & 40% Porous Pavements
M	0.5m Lake Deepening
N	0.5m Lake Deepening& 25% Green Roofs
O	0.5m Lake Deepening & 25% Green Roofs & 0.5m Lake Deepening
P	0.5m Lake Deepening & 25% Green Roofs & 0.5m Lake Deepening & 25% Green Roofs
Q	0.5m Lake Deepening & 25% Green Roofs & 0.5m Lake Deepening & 25% Green Roofs & 40% Porous Pavements
R	10% Increase in drain diameter

has a depth-damage curve associated with it. For every simulated flood, the maximum flood extent was extracted. Based upon this surface water extent, the depth, and the degree to which the properties in the catchment were flooded was identified. Each property's flood depth, flood extent, and MCM land use category was then used to estimate the damage incurred to each property. The total flood damage across the catchment was found by summing the economic damage of the individual properties.

The economic impact of flooding on the road network was assessed in a similar way. The areal extent of surface water flooding on the road network was determined and a cost per unit area was applied to calculate the cost of damage following guidance from Penning-Rowsell et al. (2013).

As noted earlier, flood benefits are defined as the economic damage avoided by implementing a flood risk reduction strategy. More formally, this is equal to the difference between the damage that is incurred by a flood under the current drainage system and the damage incurred under the adapted system by the same flood event. As such, the flood damage incurred under the current drainage system was found and used as a baseline against which the flood damages incurred on an adapted system were compared.

Standard methods of planning utilise a single future storm event to develop and assess a flood defence strategy. However, under an Adaptation Pathways approach a range of storms must be explored. This is due to the fact that pathways are chosen and can be changed based upon a yet to be unknown increase in the design storm's depth. As described earlier potential increases in design storm depth were explored at 5% intervals. Due to this, flood damage assessments were conducted at these increments. This resulted in a table of flood risk reduction benefits such as Table 6.2, where the 25% and 30% values were calculated by finding the difference in the flood damage before and after a drainage adaptation was implemented. The increments between the two known points were calculated through the use of linear interpolation.

Table 6.2: Reduction in flood damage caused by a one meter increase in lake storage for a 30 year return period events with an increase in depth

Increase in design storm rainfall depth	**25%**	**26%**	**27%**	**28%**	**29%**	**30%**
Reduction in damage caused by 1 meter increase in lake depth	£365,000	£473,000	£580,000	£688,000	£796,000	£903,000

The economic flood benefits of a solution were evaluated between the increase in depth at which a strategy was implemented until the increase in depth when it was found to be no longer effective, known as its Adaptation Tipping Point.

Conversion to Time

Financial performance analyses such as Discounted Cash Flow and Benefit-Cost Ratio require the use of annualized costs and benefits. As discussed earlier projections of how the precipitation depth of rare storms may increase were developed by the Environment Agency (2016). The increments of increases in design storm depth (such as the ones shown in Table 6.2) were converted to estimates of when they may occur, using these projections. This was conducted for all paths explored.

The economic benefits of flood risk reduction were based upon the damage incurred by a single 30-year return period storm event. For the purposes of economic analyses this lump sum needed to be converted to an annualized cash flow. The total damage was converted to an annual cash flow by dividing the total damage incurred for a single storm by its return period.

Furthermore, by converting the benefits of flood risk reduction into a cash flow tied to time as opposed to increases in the design storm, it is possible to combine this economic benefit with other financial flows.

6.3.2 Cost Estimation

All of the strategies explored are a combination of seven individual options. If a strategy is composed of multiple adaptations the total cost was taken to be the sum of the individual elements. The individual costs of the first six options in Table 6.3 were found by identifying the unit costs of the options considered. The capital expenditure (CAPEX), the cost of building the adaptations; and operational expenditure (OPEX), the cost of maintaining these adaptations were identified through a search of the literature. The costs per unit identified as well as the total CAPEX and OPEX of the options can be found within Table 6.3.

The CAPEX of increasing the trunk sewer's diameter was found through the use of standard guidance on pricing civil engineering works (AECOM, 2012). The cost of augmenting each sewer section was a function of the sewer's sub-surface depth, its increased diameter, and its length. The total cost of the sewer augmentation was then found by summing the cost of the individual sections. Thames Water provided the lengths, sizes and geometries of the sewer sections.

Table 6.3: Cost of Adaptation Options

Solution	**CAPEX/Unit**	**OPEX/Unit**	**CAPEX**	**OPEX**
Deepen lake by 0.5m	£5.41/m^3 (AECOM, 2012)	£0.5/m^3(HR Wallingford, 2004)	£66,000	£6100 /year
Deepen lake by 1m	£5.41/$m3$ (AECOM, 2012)	£0.5/$m3$ (HR Wallingford, 2004)	£132,000	£12,200 /year
Convert 25% of roofs to green roofs	£47/m^2(Royal HaskoningDHV, 2012)	£0.15/m^2 (Royal HaskoningDHV, 2012)	£1,770,000	£48,750 /year
Convert 50% of roofs to green roofs	£47/m^2 (Royal HaskoningDHV, 2012)	0.15/m^2 (Royal HaskoningDHV, 2012)	£3,540,000	£97,500 /year
Convert 20% of pavement to porous pavement	£54/m^2 (Kellagher et al., 2015)	£0.16/m^2 (HR Wallingford, 2004)	£1,700,000	£50,000 /year
Convert 40% of pavement to porous pavement	£54/m^2 (Kellagher et al., 2015)	£0.16/m^2 (HR Wallingford, 2004)	£3,400,000	£100,000 /year
Increase diameter of trunk drain by 10%	-	-	£2,340,000	£1800/year

It is known from the Adaptation Pathways at which increase in storm depth adaptations need to be implemented. Through the use of the projections in Figure 6.2 it is possible to identify the year within which the CAPEX is forecast to be spent. Additionally, it is known that the OPEX is incurred from the year that the CAPEX is implemented to the year the Adaptation Tipping Point is reached.

6.3.3 Ecosystem Benefits

The Benefits of SuDS Tool (BeST), developed by the Construction Industry Research and Information Association (CIRIA) was utilised to determine the ecosystem services provided by the SuDs solutions (Digman et al., 2016). Ecosystem services can be defined as "the benefits provided by ecosystems that contribute to making human life both possible and worth living" (Horton et al., 2016, pp.7). The BeST is the culmination of a review of 553 documents on the valuation of fourteen different ecosystem services which range from amenity to groundwater recharge (Digman et al., 2016).

Similar to the MCM, the BeST utilises a benefit-transfer method where ecosystem benefits are estimated based on similar schemes conducted in the past. The ecosystem benefits of SuDS solutions are highly context specific and influenced by the site characteristics (MWH, 2013). Given that the benefits and effectiveness of SuDS measures are highly location specific the estimated benefits may not be an accurate reflection of true-life performance.

Of the solutions explored the porous pavement and green roof adaptations were the only adaptations which provided ecosystem services. The ecosystem services that were monetized for each of these solutions and their values are displayed in Table 6.4. There were several ecosystem services such as the impact of education, health, and the treatment of wastewater that were not assessed due to a lack of data.

The benefits delivered by converting 50% of roofs to green roofs and converting 40% of pavements to porous pavements are simply double the amounts displayed in Table 6.4. It is also assumed that these values are delivered immediately and remain constant over time. This

Table 6.4: The value delivered by potential ecosystem services

Adaptation Option	Ecosystem Service Delivered	Annual Value of Individual Service	Total Annual Value of Services Delivered
25% Green Roofs	Air Quality Reduction in Building Energy Demand	£10,000 £150,000	£160,000
20% Porous Pavement	Ground-Water Recharge	£17,000	£17,000

assumption ignores the effects of a changing climate and annual changes in temperature on ecosystems services.

For the purposes of the financial analysis in this study, the annualized ecosystem services provided by the above SuDS solutions are incurred from the year that the solution is implemented until its Adaptation Tipping Point is reached.

6.3.4 Financial Analyses

Once the magnitude of the costs and benefits of the various paths were established along with the years in which they were projected to occur it was possible to conduct an economic analysis.

Discounted Cash Flow

The use of discounted cash flows to calculate the Net Present Value (NPV) of a potential project is standard engineering practice. The NPV is utilised to determine whether a project will deliver sufficient benefits to justify its costs. The majority of the benefits delivered by an element of infrastructure are delivered after it has been constructed. Discounting is used to reflect the time value of cash flows and the perception that the costs and benefits incurred in the future are of less value than those delivered in the near term. To reflect this, the costs and benefits delivered in the future are discounted utilising Equation 1 to determine their “present value”. The summation of the present values of a project’s costs and benefits determines the project’s NPV.

$$NPV = \sum_{t=1}^{T} \frac{X_t}{(1+r)_t} \tag{6.1}$$

Where T represents the length of the project's lifetime in years, X_t is a cost or benefit incurred in a year by the project and r is the discount rate. Following the UK Treasury's Green Book, economic appraisals of public infrastructure projects utilise a standard discount rate of 3.5% while projects over 30 years in length utilise a discount rate that declines as the project's duration is increased (Lowe, 2008).

Benefit-Cost Ratio

The Benefit–Cost Ratio (BCR) of a project is the ratio of the total undiscounted benefits to the total undiscounted costs for a proposed project. It has been noted that given the limited resources for urban drainage interventions the BCR may be a more useful metric than NPV for judging the cost-effectiveness of a potential project (Defra, 2010).

6.4 Results & Discussion

The Benefit-Cost Ratios and Net Present Values for all paths considered are displayed in Table 6.5. These financial analyses utilised the central climate change scenario to convert the pathways from percentages to years. This scenario dictated the rate at which precipitation depths increased which in turn defined the operational lives of the solutions; in turn affecting OPEX, total flood risk reduction benefits, and ecosystem services.

Table 6.5: Results of the Financial Analyses for the Paths Explored

Path	**NPV**	**BCR**
A	£15,300	1.18
B	£-1,140,000	0.19
C	£-£1,330,000	0.58
D	£-2,660,000	0.57
E	£-987,000	0.54
F	£-268,000	1.04
G	£-965,000	0.79
H	£-2,300,000	0.67
I	£3,120,000	2.81
J	£3,170,000	2.75
K	£2,470,000	1.76
L	£1,130,000	1.14
M	£-138,000	2.37
N	£-777,000	0.43
O	£-737,000	0.49
P	£-1,720,000	0.35
Q	£-2,770,000	0.52
R	£-2,230,000	0.02

The results displayed show that the vast majority of the paths through the Adaptation Pathways result in a negative Net Present Value. Under a changing climate the ability for a drainage adaptation to deliver benefits expires before it has had sufficient time to offset its costs.

Climatic stationarity allowed for extended periods during which the benefits provided by a flood alleviation scheme could accumulate and deliver a return on the capital investment. However, under conditions of climate change the design life of infrastructure is shortened. Over these shortened life times it is difficult for sufficient benefits to be accrued for the capital expenditure to be offset. It may therefore be necessary to develop oversized solutions in order to maintain a sufficiently long design life such that a return on investment can be generated. Alternatively, the new reality of climate change may be that flood defence assets will deliver a lower return on investment than in the past.

The lack of return on investment is further reflected in the poor benefit to cost ratios (BCR). In recent years, a benefit to cost ratio (BCR) of 8:1 has been applied to flood defense related decision-making in England (Environment Agency, 2009). The maximum BCR for the paths considered is equal to only 2.81. Until recently, a proposed flood scheme needed to demonstrate a lower BCR of 1:1. The initial analysis displayed here would indicate that the current BCR threshold might need to be revised downwards to a level more consistent with its historic precedent in order for the necessary adaptation to take place.

The order in which options are implemented can have a profound impact on the Net Present Value of a pathway. There were four pathways that lead to the implementation of the strategy with the highest ATP; these were D, H, L and Q. The BCRs for these paths were 0.57, 0.67,1.14, and 0.52 respectively. The NPVs for these paths were -£2,660,000, -£2,300,000, £1,130,000, and -£2,770,000 respectively. This strategy consists of 50% green roof coverage, deepening the lake by one-meter, and a conversion of 40% of road areas to porous pavements. Even though all four pathways were found to be technically sound, the order in which adaptation options were implemented resulted in radically different NPVs. Of these four paths, only path L consisted of the combination of solutions that resulted in the maximum ATP being reached while also resulting in a favorable Benefit Cost Ratio and Net Present Value. This path consisted of converting 25% of roofs to green roofs, followed by a 0.5m deepening of the lake, followed by another 0.5m deepening of the lake, converting another 25% of roofs to green roofs, and finally converting 40% of roads to porous pavements.

Even though all pathways delivered the requisite level of flood protection with the same adaptations there was a huge variation in financial performance. This highlights the need to keep path dependence in mind when making decisions under conditions of deep uncertainty. The presented analysis suggests that the choice of paths through a set of Adaptation Pathways could be highly constrained once the financial viability of different strategies is considered.

6.4.1 Comparison to Classical Analysis

In order to assess the advantages and disadvantages of the pathways methodology, a NPV and BCR analysis of a predict-then-act assessment was undertaken. This builds upon a predict-then-act analysis conducted within Chapter 5.

The lifespan of an adaptation to the drainage system was assumed to be 50 years, based upon the high scenario for change in the design storm's rainfall depth, in 50 years time there will be a 28% increase in the depth for the design storm. Under such conditions, the enlarging of the trunk sewer is the simplest solution to address the gap in flood protection. A Discounted Cash Flow and Benefit-Cost Ratio analysis was conducted on this adaptation. The cash flows utilised for the DCF were the flood risk reduction benefits, the CAPEX, and OPEX of the solution. This resulted in an analysis which found that the NPV to equal £-2,230,000, with a BCR of 0.02. This is clearly a highly undesirable result. The other solutions explored in this analysis with similar CAPEXs were able to offset their costs through the use of longer payback periods and large amounts of value derived from ecosystem services.

6.4.2 Appropriateness of Methods

Several different appraisal tools were utilised in this study in contexts outside of their typical applications. Previously these methods were used for estimates of deterministic storms, in this work they were extended for use across ensembles of flood events.

The Multi Coloured Manual provided a highly granular and efficient methodology of assessing economic flood risk benefits. The scope of the study was constrained to consider only damage incurred to property and to the road network. Indirect and intangible costs were not considered within this study. Future work may attempt to quantify these more ephemeral costs, such as the loss of a historic site. There is the potential that a more thorough analysis of the transport related flood damages could drastically improve the ratio of benefits to costs. Such an analysis would require detailed data on traffic flows, which are outside the current scope of this study. This could significantly improve the benefits reaped by the adaptation strategies. Other damage estimation methods that take into account the relatively high property prices of London could also significantly increase the flood risk reduction benefits of the solutions; thereby improving the financial viability of the paths explored.

There are significant assumptions made within this study with regards to land use development in the catchment. It is assumed that land use in the future will remain similar to the present. These issues could be addressed by conducting a land use change study. However, this would result in the need for a further amount of computational simulations. DMDU analyses, which generate Adaptation Pathways are characterized as being computationally intensive and the addition of further simulations would result in an even greater computational expense.

The Benefits of SuDs Tool offers a rapid and simple method to quantify the ecosystem services of the solutions explored. However, this methodology does contain limitations. The calculated benefits from BeST do not take into account the changing value of services over time due to climate change. Furthermore, it is known that ecosystem services vary even under conditions of climatic stationary (Kellagher et al., 2015). More ecosystem services could be valued in the future with the use of BeST if the necessary data and projections were made available; these added benefits could also improve dramatically the financial performance of the paths explored.

6.5 Conclusions

From the preceding analysis, it has been presented that is possible to deliver a high level of adaptation, for up to a 44% increase in rainfall depth, while also delivering a positive NPV and BCR. However, the return on investment delivered by most of the solutions explored is negative. Such information aids in delivering improved decision making for sustainable urban water management, as it is now known that even though all paths deliver the necessary level of flood protection only a minority of paths deliver a return on investment.

This chapter investigates for the first time how a set of pre-existing Adaptation Pathways can be financially assessed. Of particular scientific interest was the conversion of benefits linked to increases in depth to benefits linked to time; allowing for these financial flows to be combined with economic flows tied to time.

The paths that did deliver a positive return on investment in many cases did so due to the advantageous order in which potential adaptations were ordered. The order in which solutions are implemented is critical in whether or not a positive NPV is generated. Therefore it is clear that the economic information provided delivers improved decision making information for sustainable urban water management. Of the solutions that did show positive returns, the

BCR was lower than what is mandated of flood defence projects by the UK's Environment Agency. This would indicate that adapting urban drainage systems to the risks of increased storm depth will prove to be costly and that the minimum BCR required for a flood protection scheme to go forward may need to be adjusted downwards to reflect this new reality.

Chapter 7

Evaluation of Adaptation Pathways under Uncertainty

7.1 Introduction

The economic assessment of Adaptation Pathways is a burgeoning research area due to the growing prevalence of DMDU techniques. Adaptation Pathways have been evaluated through the use of deterministic climate change scenarios. However, such methods ignore the uncertainty surrounding projections of climate change. By not exploring this uncertainty the effect of errors in prediction on a path's financial performance are ignored. Furthermore, by utilising methods for evaluating projects under uncertainty a more robust economic evaluation of adaptation pathways is achieved. This results in a metric of financial performance that communicates the range of potential financial performances that could occur. This added information can result in improved and more robust decision making. This chapter is based on the paper Babovic et al (Under Review).

The design of long-term infrastructure systems is hampered by the presence of multiple interacting and poorly characterized uncertainties. The resulting condition, known as deep uncertainty, obfuscates whether decisions made in the present will remain viable in the future. For situations of deep uncertainty, appropriate Decision Making under Deep Uncertainty (DMDU) techniques should be used, as traditional planning techniques are not appropriate (Walker et al., 2013). Globally, DMDU techniques are increasingly being used to develop adaptation strategies across a number of sectors. These analyses frequently result in a set of Adaptation Pathways. These pathways communicate to decision makers how short term decisions can act as elements of larger adaptation strategies and the limits to the effectiveness of individual solutions and strategies.

As noted earlier, Adaptation Pathways have been generated for a number of different fields. While these Adaptation Pathways communicate how a system can be adapted to deliver system reliability in the future, on their own they do not communicate the relative costs and benefits of these pathways. By assessing a set of pre-existing Adaptation Pathways once can be sure that the pathways will deliver a reliable level of service and that the generated pathways weren't compromised by financial considerations.

In Chapter 6, the economic assessment of a set of adaptation pathways was undertaken. These Adaptation Pathways were originally developed due to a need to adapt an urban drainage system to climate change. The evaluation of the Adaptation Pathways was conducted by using the "most likely" increase in design storm depth as developed by the Environment Agency (2016). This climate change scenario dictated the length of time a drainage adaptation strategy was effective; in turn this affected the value of ecosystem services, OPEX, and flood benefits that could be reaped. However, this economic analysis ignored the uncertainty surrounding forecasts of how precipitation patterns will change. It is hypothesized that a method of economic evaluation that thoroughly explores uncertainty would result in a more robust economic analysis and lead to improved decision making.

To address the uncertainty surrounding projections, methods for economically evaluating project under uncertainty were used to generate a more robust financial analysis of the Adaptation Pathways. These methods for evaluation under uncertainty were originally developed as part of real options analyses (Wang and Neufville, 2004). The use of such methods allows for the identification of how a drainage adaptation will financially perform across a range of futures and whether its performance is sensitive to errors in projections. However, unlike real options where maximising financial performance is the primary objective of the analysis and the driver of analytical choices; here we are applying real options methods to a set of pre-existing pathways developed from a physically based model where engineering performance was the main metric of success.

7.2 Jensen's Inequality

The economic evaluation of Adaption Pathways in Chapter 6 was based on the central estimate of how an individual storm depth will increase. The central scenario, even though it represents the mean projection of future conditions does not necessarily reflect the average financial performance of a drainage adaptation. This is due to what has been termed the "flaw of averages" (Savage, 2009) more formally known as Jensen's inequality (Jensen, 1906).

The flaw of average refers to the common but mistaken assumption that evaluating a project around average conditions delivers an indication of the average financial performance of a system (de Neufville and Scholtes, 2011). This assumption only holds true if all the relevant relationships explored in the economic analysis are linear. Mathematically this can be expressed as shown in Equation 7.1.

$$E[f(x)] \neq f(E[x]) \tag{7.1}$$

Where *f(x)* is a non-linear function that defines the value delivered by a project over a space of parameters x.

The economic assessment of urban drainage adaptation strategies contains numerous non-linearities. The flood risk reduction benefits are non-linear due to the non-trivial relationship between incident precipitation and urban surface water extent. Additionally, there are discontinuities in cash flows; multiple costs and benefits are linked to when and if solutions are implemented. For example, the ecosystem benefits and maintenance cost of SuDs are only incurred after the construction of this infrastructure has occurred. Lastly, different climate change scenarios affect the length of time that a piece of infrastructure delivers reliable service; thereby affecting the total benefits and costs incurred by an adaptation strategy.

Furthermore, by focusing on average conditions one neglects the impact of events with remote probabilities. A cost-benefit analysis geared to average conditions ignores the effects of negative events and the ability to make use of opportunities (Taleb et al., 2012).

7.3 Methodology

7.3.1 Generation of Adaptation Pathways

In Chapter 6, the Adaptation Pathways for an urban drainage system were assessed. The pathways were developed for a case study in the Cranbrook Catchment in the North East of London. The Adaptation Pathways were developed for changes to the thirty-year return period storm, displayed in Figure 7.1.

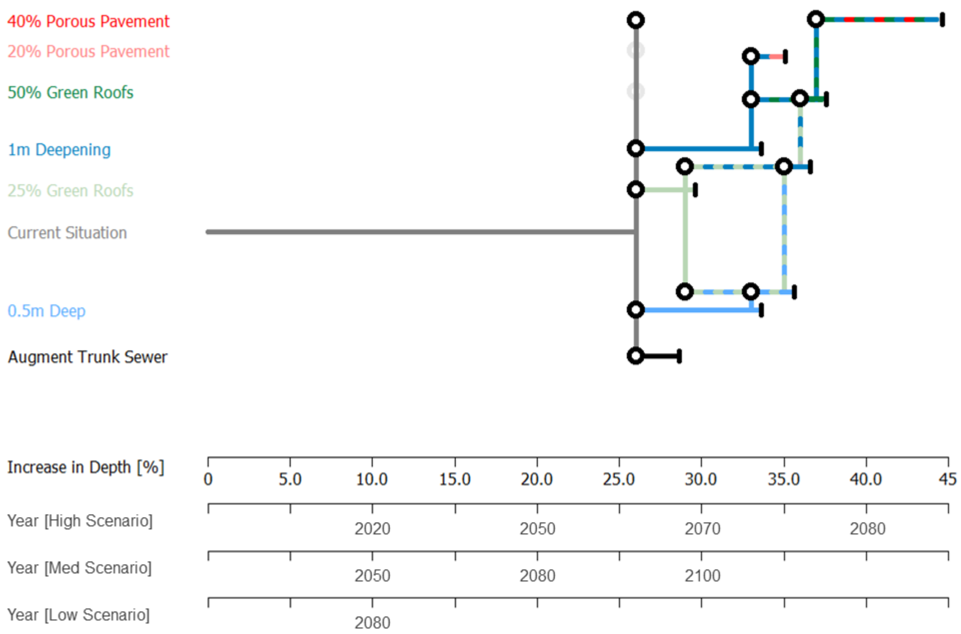


Figure 7.1: Adaptation Pathways for increase in depth of 30 year return period storm and no increase in peakedness

In Chapter 6, the pathways presented were economically assessed for one climate change scenario. All of the paths within Figure 7.1 were identified. This resulted in a set of 18 paths;

summarised in Figure 7.2.

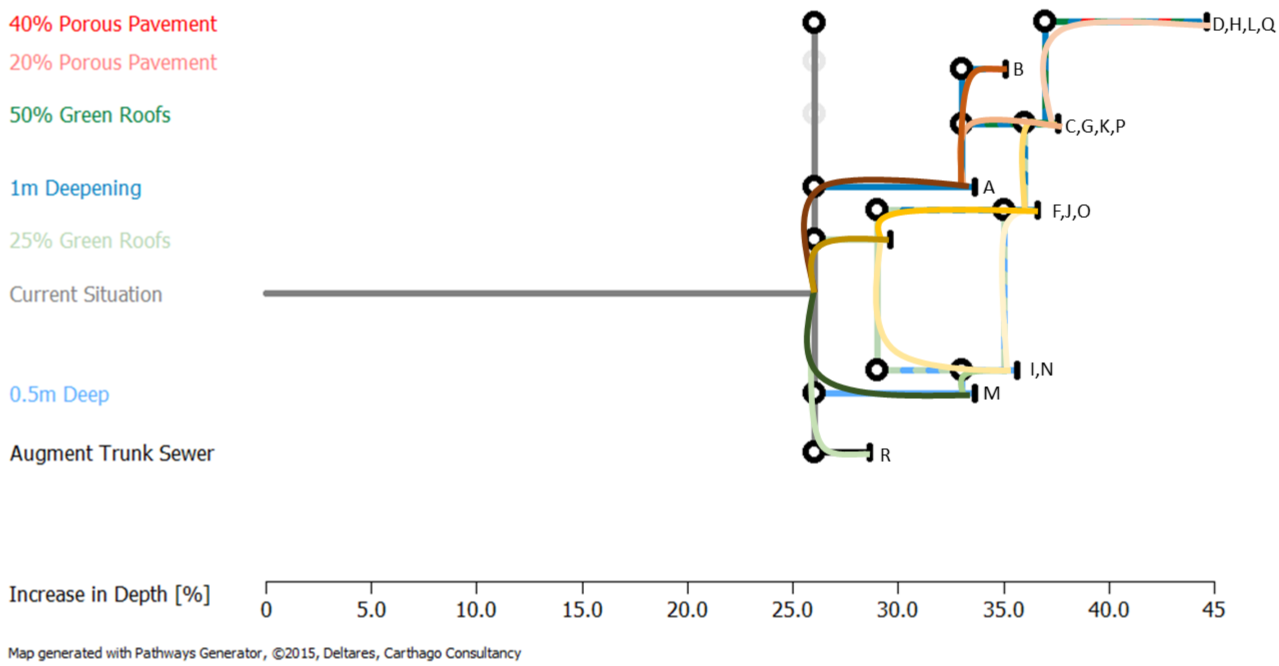


Figure 7.2: Potential paths through the Adaptation Pathways, colours represent individual paths which all have unique sequences of adaptations

7.3.2 Deterministic Evaluation of Paths

Adaptation Pathways are developed in such a way that they are rooted in a driver of change; in this case increases in the design storm's depth. Due to this, the costs and benefits linked to increases in storm precipitation depth were initially addressed. Below is a summary of the work conducted in Chapter 6, which provides the basis for the evaluation under uncertainty.

The flood risk reduction benefits were assessed using the Multi-Coloured Manual (Penning-Rowsell et al., 2013). Every structure within the Cranbrook case study was assigned a MCM land-use code. Every MCM land-use code has an associated depth-damage curve associated with it. To evaluate the effectiveness of an adaptation, design storms with increasing depths in 5% increments were used to stress test adaptations. The maximum surface water extent for each potential storm was extracted from Infoworks ICM. The surface water extent allowed for the identification of the depth and extent to which structures within the Cranbrook were flooded. By utilising information regarding the inundation of the buildings and applying these to depth-damage curves it was possible to find the damage incurred by a storm with a given increase in precipitation depth. The flood risk reduction benefits of a drainage strategy are defined as the difference in flood damage incurred by a storm on an adapted drainage system and the current system. As such, the flood damage incurred on the current drainage system was used a baseline against which the adapted drainage system was compared. This resulted in a relationship that linked the flood risk reduction benefits of a strategy to increases in design storm depth.

However, financial analyses are based upon annualised cash flows not changes in a storm's precipitation depth. An algorithm was developed which converted the pathways from the form presented Figure 1; where the pathways are organized in relation to percentage increases in storm depth, to pathways rooted in time. A forecast of how the precipitation depth of storm events may increase was used to convert the Adaptation Tipping Points of the Adaptation Pathways to estimates of when these ATPs may be reached. This provided a potential start date, end date, and length of time during which the adaptation is effective. This information provided the skeleton upon which other cash flows such as capital costs, maintenance costs, and ecosystem services were placed.

The capital expenditure (CAPEX) and operational expenditure (OPEX) of the potential adaptations were derived from unit costs of these adaptations. The value of the ecosystem services provided by potential Sustainable Drainage systems solutions were evaluated using the Benefits of Suds tool (BeSt) (Digman et al., 2016). These cash flows, along with the flood risk reduction benefits were combined to find the Net Present Value and Benefit-Cost Ratio of potential pathways. The time value of money was accounted for through the use of discount factors provided by the Treasury Green Book (Lowe, 2008).

By utilising only the central projection of climate change the effects of forecast uncertainty on financial performance were ignored. To deliver a more robust assessment of financial performance methods for evaluating projects under uncertainty were applied.

7.3.3 Economic Evaluation of Pathways Under Uncertainty

Real Options is a method of planning under conditions of uncertainty. The concept of real options was originally developed by Trigeorgis (1996) as a method of utilising flexibilities present in an engineering system to minimise exposure to potential risks while allowing for the ability to take advantage of opportunities. The aim of real options is to maximise the Expected Net Present Value (ENPV) of a project, as such, this method is highly focused on the financial performance of a potential engineering project. The Real Options methodology has in the past been applied to the design of numerous urban drainage adaptations (Buurman and Babovic, 2016; Wong, 2013; Zhang and Babovic, 2012). However the methods that underpin Real Options have not been used to assess a set of Adaptation Pathways.

The basis of real options is that potential projects are assessed by how they financially perform across a range of futures. Similar to DMDU methods, numerous simulations of the future are generated and applied to a potential adaptation. For each of these simulations the financial performance of the project is assessed. This results in a financial performance metric for every future explored. A meta-analysis is then performed on this set of financial metrics. This bottom-up method of assessing financial performance delivers a more robust assessment of how a project will financially perform (de Neufville and Scholtes, 2011). Such a method addresses the problem of Jenesen's inequality and allows for an accurate assessment of financial performance under uncertainty. To conduct the evaluation under uncertainty of the paths shown in Figure 7.2; 200 projections of how the depth of rare storms may increase were developed based upon Environment Agency (2016). These 200 projections are displayed in Figure 7.3. Colours are used to differentiate between projections and do not denote any other properties.

The 200 futures were applied against the algorithm described earlier. This resulted in a set of 200 Net Present Values and Benefit-Cost Ratios for all 18 paths identified in Figure 7.2. These metrics were then used to generate Empirical Cumulative Distribution functions such as the one shown in Figure 7.4. The empirical cumulative distribution functions (ECDF) for all of the paths, for both NPV and BCR, are displayed in Appendix B.

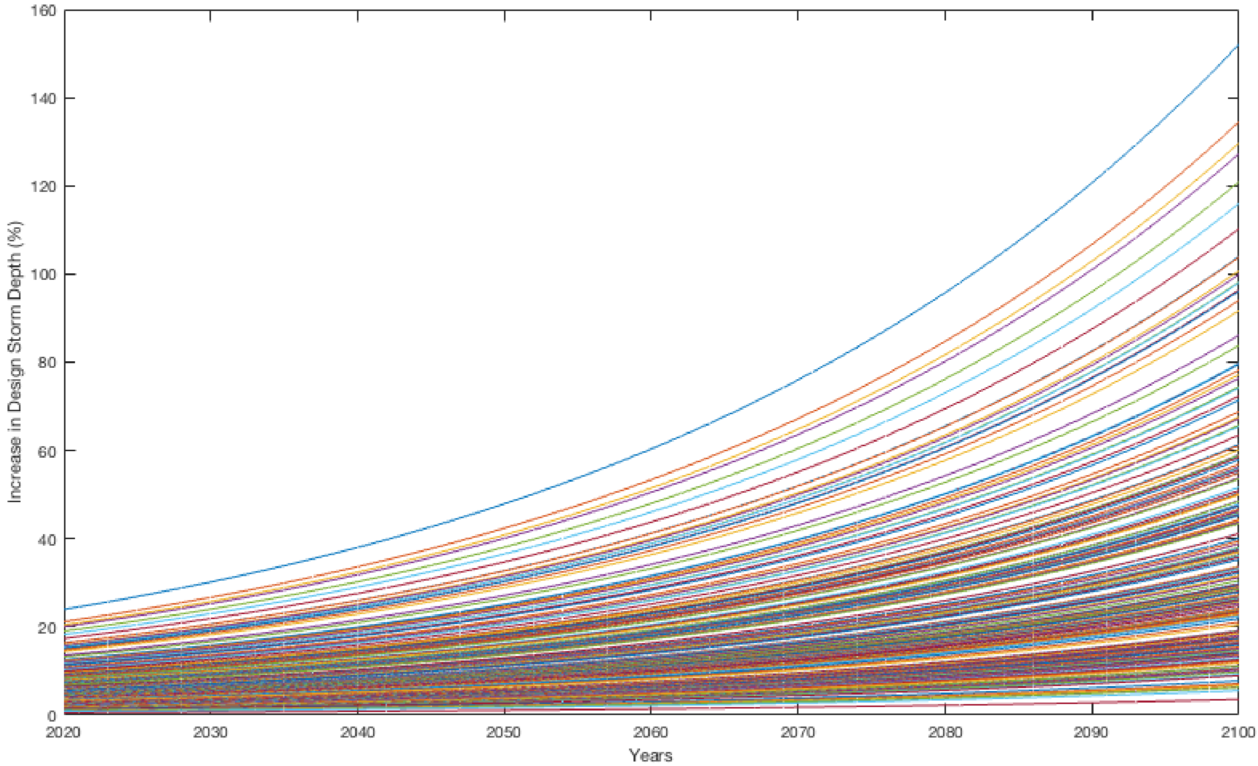


Figure 7.3: Two hundred projections of increases in the precipitation depths of rare storm events, colours are used to denote different projections

The financial performances for each future were then used to investigate how each path will perform across this bundle of futures. Finding the means of the samples resulted in the Expected Net Present Values (ENPV) and Expected Benefit Cost-Ratios (EBCR) being calculated. Additionally, the standard deviation of the Net Present Values and Benefit-Cost Ratios were determined; quantifying the range of financial performances present across the futures explored.

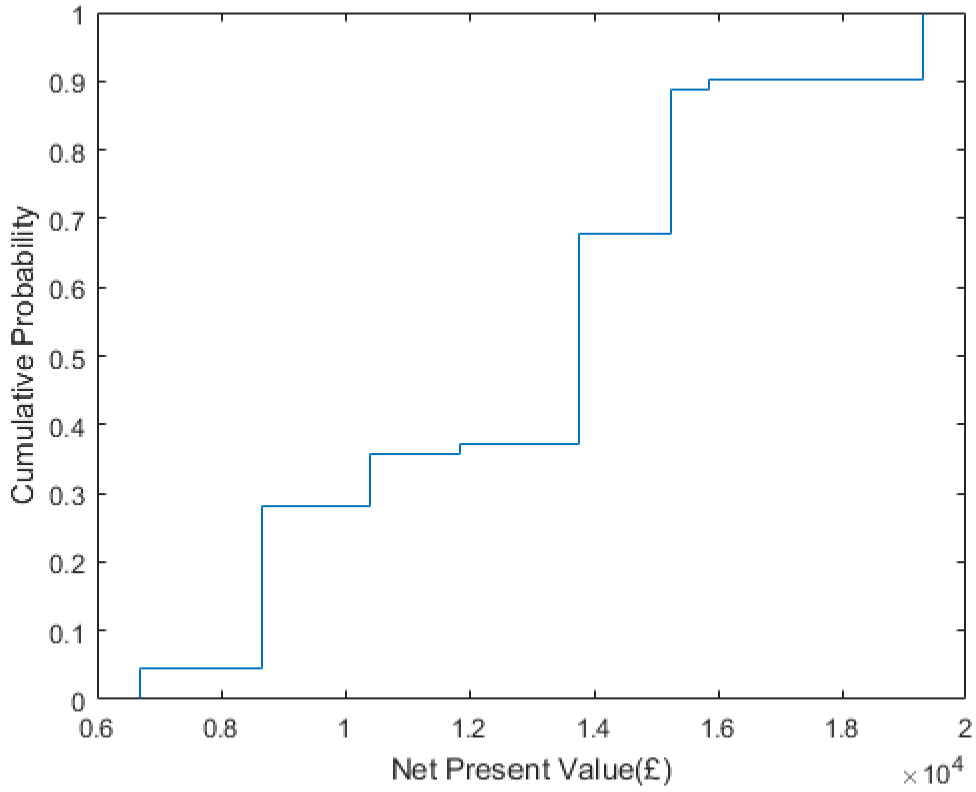


Figure 7.4: Empirical Cumulative Distribution of the 200 NPV evaluations for Path A

7.4 Results

The aggregated financial performances of the potential paths across the 200 futures are displayed in Table 7.1.

The results displayed in Table 2 show the results from Table 1 compared to the deterministic assessment developed in Chapter 6. The difference columns presents the absolute difference between the metric derived by deterministic methods and the metric calculated under uncertainty. Negative values indicate that the metric calculated by deterministic methods over-estimated the metric when compared to the one calculated under uncertainty. To provide further context the difference between the calculated metrics were normalized by dividing by the standard deviation of the NPV or BCR of that path.

Table 7.1: Financial Metrics Calculated under Uncertainty

Path	Expected Net Present Value	Standard Deviation of NPV	Expected Benefit-Cost Ratio	Standard Deviation of BCR
A	£13,000	£3,500	1.17	0.017
B	-£1,170,000	£22,000	0.19	0.006
C	-£1,370,000	£32,000	0.57	0.014
D	-£2,700,000	£44,000	0.58	0.014
E	-£1,000,000	£52,000	0.51	0.037
F	-£260,000	£26,000	1.05	0.015
G	-£1,000,000	£61,000	0.74	0.023
H	£2,400,000	£71,000	0.66	0.012
I	£3,250,000	£127,000	2.85	0.059
J	£3,320,000	£125,000	2.79	0.055
K	£2,510,000	£122,000	1.75	0.034
L	£1,170,000	£114,000	1.14	0.016
M	£130,000	£5,000	2.34	0.034
N	-£760,000	£33,000	0.46	0.037
O	-£690,000	£24,000	0.55	0.028
P	-£1,720,000	£23,000	0.35	0.008
Q	-£2,840,000	£49,000	0.51	0.013
R	-£2,240,000	£5,300	0.02	0.003

With regards to the ENPV ten out of eighteen paths were over predicted. Once the over and under predictions of Net Present Values were normalized in relation to their absolute values it was found that the over and under predictions were of similar magnitude to one another; the average under prediction was equal to 3.11% of the ENPV in comparison to 3.12% for the over-prediction.

The EBCR resulted in a lower BCR than the one estimated via deterministic methods for eleven out of the eighteen pathways considered. This would suggest that BCR estimations under uncertainty are likely to result in a worse financial performance than the performance calculated using the central deterministic projection. This is further reflected in the normalized average over and under calculation: the average over prediction was 2.89% while the average under prediction was 3.17%.

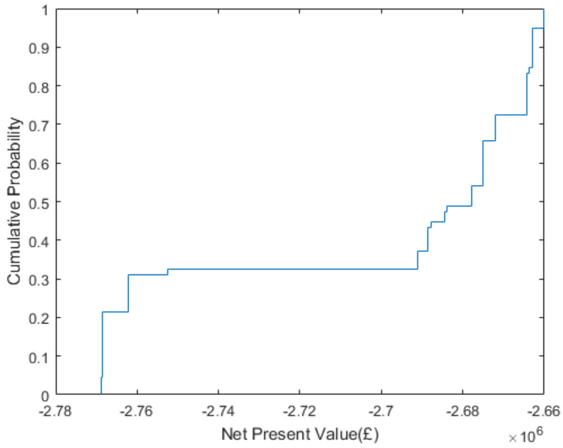
The standard deviations of both financial performance metrics were small relative to their mean values. As such, for all of the pathways considered there were no 'borderline' cases that could experience failure or success depending upon which scenario was experienced. The relatively small standard deviations of performance would also indicate that the financial performances

Table 7.2: Comparison of results of evaluation under uncertainty to deterministic results

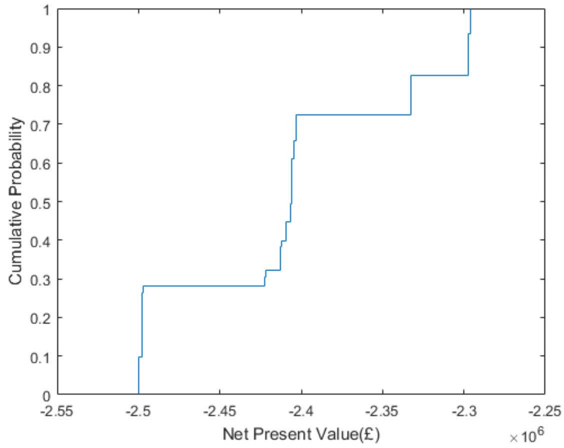
Path	Difference in NPV	Normalised Deviation from ENPV	Difference in BCR	Normalised Deviation from EBCR
A	£2,400	0.70	-0.015	0.88
B	-£29,000	1.34	-0.002	0.39
C	-£40,000	1.24	-0.006	0.46
D	-£39,000	0.88	0.009	0.69
E	-£39,000	0.75	-0.027	0.74
F	£6,200	0.24	0.005	0.33
G	-£100,000	1.80	-0.046	1.97
H	-£110,000	1.53	-0.012	0.96
I	£130,000	1.03	0.042	0.71
J	£150,000	1.24	0.043	0.79
K	£40,000	0.33	-0.003	0.09
L	£40,380	0.36	0.0001	0.01
M	-£5,200	1.03	-0.030	0.88
N	£19,000	0.57	0.034	0.92
O	£43,000	1.81	0.053	1.91
P	£3,600	0.16	-0.002	0.29
Q	-£73,000	1.47	-0.001	0.11
R	-£4,300	0.81	-0.002	0.81

of the paths are insensitive to the effects of potential futures.

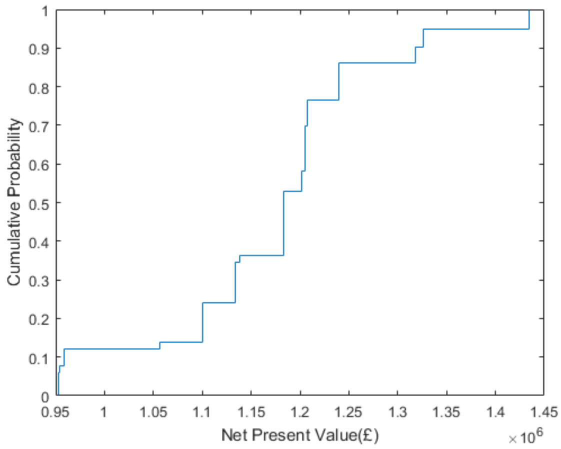
Following from Chapter 6, the order in which options are implemented can have a profound impact on the Net Present Value of a pathway. There were four pathways that lead to the implementation of the strategy with the highest ATP; these were D, H, L and Q. This strategy consists of 50% green roof coverage, deepening the lake by one-meter, and a conversion of 40% of road areas to porous pavements. Even though all four pathways were found to be technically sound the order in which adaptation options were implemented resulted in radically different NPVs. Of these four paths only path L consisted of the combination of solutions that resulted in the maximum ATP being reached while also resulting in a favorable BCR and NPV. Figures 7.5 and 7.6 show the empirical cumulative distribution functions for the financial performance of these four paths.



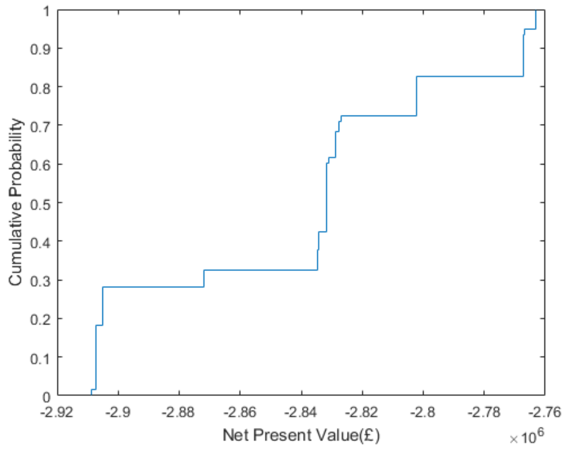
(a) ECDF for the NPV of path D



(b) ECDF for the NPV of path H



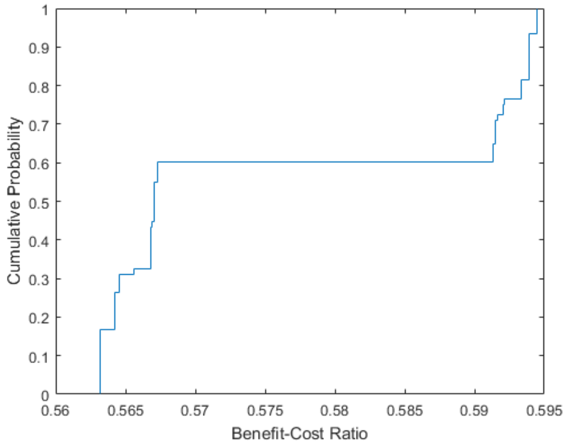
(c) ECDF for the NPV of path L



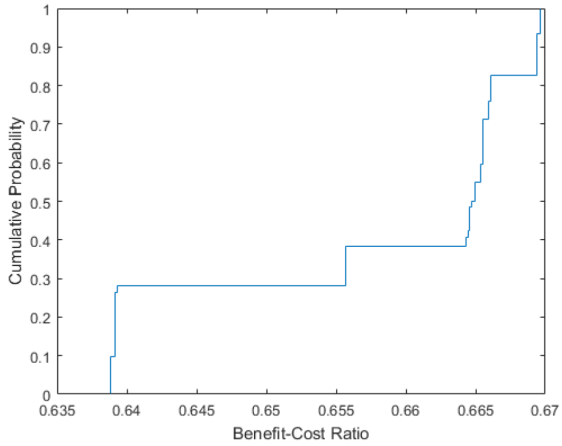
(d) ECDF for the NPV of path Q

Figure 7.5: ECDFs for the NPVs of paths D,H,L, and Q

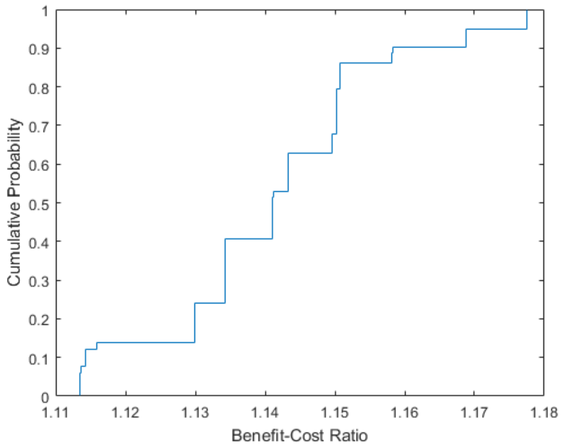
All four of these paths resulted in clearly positive or negative results. This would suggest that the effects of uncertainty can not counteract the effect of path dependence. This would indicate that at least for this case study the order in which adaptations are implemented is paramount to financial success and the effect of precipitation uncertainty is a distant secondary consideration.



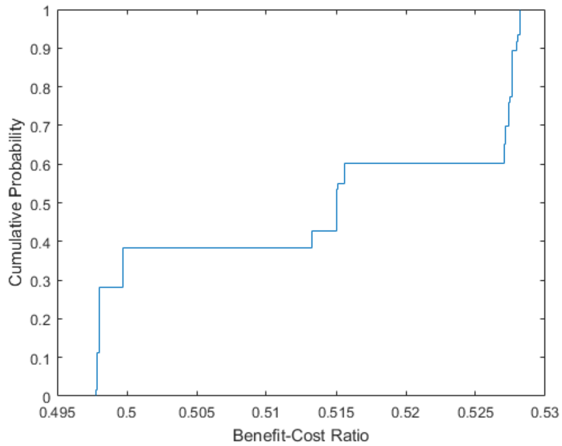
(a) ECDF for the BCR of path D



(b) ECDF for the BCR of path H



(c) ECDF for the BCR of path L



(d) ECDF for the BCR of path Q

Figure 7.6: ECDFs for the BCRs of paths D,H,L, and Q

7.5 Discussion

Two hundred simulations of the future were generated and used to assess the financial performance of the pathways. These simulations were developed by sampling from a probability density function developed by the UK Environment Agency (2016) using a Monte Carlo method.

While these two hundred storms captured the majority of potential behaviors, several extreme cases exist which were not explored in this analysis. Given the number of scenarios used any futures that weren't explored would be considered to be rare. Infrastructure design decisions are unlikely to be made based upon events of remote probabilities occurring. Therefore, while further exploration of potential futures would allow for better characterization of tail events and a more robust exploration of a project's ENPV; it is unlikely that these tail risks will impact decision making. Furthermore, from the low standard deviation of financial performances it can be observed that the financial performances of the paths exist in a narrow range. This would suggest that the further exploration of potential futures would not notably shift the distribution of the financial performances.

The process of evaluating projects under uncertainty requires the use of probability density functions. However, deep uncertainty denotes an inability to accurately assess the probability of future events occurring. This presents a contradiction. To address this, a broad exploration of futures was utilised. This breadth is best exhibited with regards to the more extreme climate change scenarios, where the short-term increases in rainfall depth are very unlikely to occur without a large stepwise change in precipitation patterns. Furthermore, the low standard deviation of performance would indicate that performance will be fairly insensitive to future conditions. While this method does not fully address the issue of deep uncertainty in practice the resulting analysis is sufficiently robust to be of value for non-predictable future conditions. Additionally, the results of the analysis gives an indication of the relative financial performance of the paths.

The use of evaluation under uncertainty results in a more robust economic analysis than deterministic methods. It is clear that the financial performance of paths determined by the deterministic method is not equal to the financial performance of the paths assessed under uncertainty. The average deviation of the deterministic method from the ENPV was equal to 96% of that path's standard deviation. For the BCR the deviation average deviation from the EBCR was equal to a distance of 0.719 standard deviations. These deviations would imply that Jensen's inequality is in effect for the problem of urban drainage adaptation. Based on this it can be assumed that the Expected Net Present Value and Expected Benefit-Cost Ratios estimated from the ensemble of futures is a more reliable assessment of financial performance than the assessment of pathways developed with the use of the deterministic projections. Furthermore, the range of futures explored allows for improved decision making by giving policy makers a range of future performances that could occur.

The evaluation of performance under uncertainty also allows for the creation of the defining characteristics of antifragility. By having an understanding of the size of the potential benefits versus the size of the potential costs, systems can be designed in a way such to maximise performance under uncertainty.

7.6 Conclusions

The evaluation of pathways under conditions of uncertainty can be improved upon by evaluating the financial performance of an adaptation over many futures. By undertaking such a bottom-up analysis the resulting financial metrics are more robust and deliver a better indication of the financial performance of a project under conditions of change. In particular, by estimating the distribution of NPV choices infrastructure choices can be made which maximises benefits while minimising risks allowing for antifragility.

By evaluating performance under uncertainty it is possible to derive an assessment of the range of potential financial performances. For the paths explored it was found that there were no edge cases where the success of a project was dependent upon which future scenario was explored. In turn, this gives decision makers a better appreciation for the uncertainty present within these calculations and the range of potential outcomes that they may face. This allows for decision makers to be made aware of the risks and opportunities provided by potential adaptations thus allowing for improved decision making.

Chapter 8

Conclusions

8.1 Summary of Work

- This thesis developed a new methodology of Decision Making under Deep Uncertainty, building upon the Adaptation Tipping Points methodology.

- This new method allowed for the exploration of multiple potential changes to the design storm for the first time in a DMDU context.

- Adaptation Pathways were developed for a highly urbanised catchment experiencing multiple drivers of change.

- The Adaptation Pathways highlighted the importance of drainage capacity and infiltration and the need for potential drainage adaptation strategies to address both factors.

- Upon comparison with a standard predict-then-act analysis it was shown that Adaptation Pathways deliver a much better appreciation of how solutions can act as incremental elements of a long-term adaptation strategy.

- A novel methodology for assessing the economic viability of Adaptation Pathways for flood protection was developed.

- This economic analysis explicitly took into account the value of flood protection benefits as well as the eco-system services provided by blue-green solutions.
- The economic assessment was extended by investigating the effects of uncertainty on the financial performance of the potential pathways.
- The work presented in this thesis is unique in its scale, the exploration of the two drivers of change resulted in 121 potential storms. Seven potential solutions were then identified to address the ATPs being reached; when combinations of options were considered this resulted in 53 strategies. Each of these 53 strategies was exposed to the 121 storms resulting in a total of 6534 model runs. This dwarfs previous ATP analyses which utilised only a few dozen model runs for their analysis.

8.2 Conclusions and Key Contributions

- The Adaptation Pathways showed the relative importance of the drivers explored and how different drivers result in different Adaptation Pathways.
- It was found that increases in design storm depth are relatively important in comparison to increases in rainfall peakedness.
- It is shown that the order in which solutions are implemented affect the cost-benefit analysis of the solutions to an extremely large extent
- Jensen's inequality is shown to be in effect, therefore evaluation under uncertainty is required to develop an accurate assessment of financial performance.
- The concept of antifragility was applied to infrastructure planning for the first time. This proposed system's attribute allows for infrastructure systems to benefit from uncertainty and use unexpected shocks as learning opportunities.
- This thesis has resulted in four journal articles being submitted for publication under peer review; at the time of writing one has been published, one accepted for publication, while the remainder remain under review.

- The developed lead to presentations at six international conferences in Europe and America; with a dozen presentations within the UK.

- In 2017, I was nominated for the Paul-Harremoes Award for young researchers at the International Conference on Urban Drainage. This nomination was based upon the novelty of my work and its contributions to the urban drainage community.

- Thames Water, the water utility that serves the majority of the South East of England and London aims to use the methodology shown in this thesis to develop their long-term drainage adaptation plan.

8.3 Future Work

There are several avenues for further investigation and future work.

Repeating the analysis with a different metric of system failure may result in a different set of Adaptation Pathways being generated. Different metrics to be potentially explored include property damage, the total flood volume surcharged by the drainage system, or the prevalence of basement flooding. The surcharging of manholes was used in this thesis as the failure criterion because it is a governmental standard, however it is an imperfect metric that may not necessarily reflect the effects that climate change may have on people's lives. Metrics related to property damage from flooding are much more relevant to citizens living within the catchments. Comparing the Adaptation Pathways created by different metrics may result in novel insights into the behaviour of drainage systems. Additionally, metrics that are more focussed on flood damage could result in a better level of financial performance of adaptation strategies.

With regards to modelling, there is much to explore with regards to how urban drainage systems are modelled within a DMDU context. Particularly with regards to semi/fully-distributed physics and the appropriate time-step to be used. This is critical in establishing the appropriate trade-off between computational expense and the physical replication of processes. The modelling of SuDs solutions within Infoworks ICM could be more fully developed in the future;

currently SuDs solutions were implemented by changing the porosity of various elements of the Infoworks models. By utilising more physically based SuDs models within Infoworks it would be possible to have a better assessment of this infrastructure's performance under change.

In the future, should this study be repeated, it would be best to use a finer exploration of increases in design storm depth. Within this thesis, 5% increments were used, however, upon evaluating the results we found this step to be too coarse. In future analyses of the Cranbrook it would be more beneficial to use steps of 2.5% or 2%. While increments of this size are appropriate for the Cranbrook Catchment, it is not known whether this 2.5% step would be appropriate for all catchments and drainage systems. Upon discussing this issue with members of academia and industry there is a general agreement that 5% increments are too coarse. However, alternative increments to be used vary widely from 0.25% to a few percentage points. A brief sensitivity analysis at the start of a DMDU analysis would allow for a more appropriate increment to be chosen. This would also allow for a more informed trade-off to be made between the exploration of drivers and the computational cost that could be incurred from exploring futures.

Applying the ATP method to a combined sewer system would raise novel questions regarding how to manage, model, and plan for uncertainties population growth and the impact of people on wastewater discharges into the system. This body of research is of particular importance to those water utilities that operate combined sewer systems.

The effects of land use were not explored beyond the proxy of increasing the design storm's peakedness. Explicitly modelling how urbanisation may develop in the catchment through the use of land-use change models would be of great practical use in identifying which regions of the Cranbrok are more likely to experience flooding.

Currently, rainfall events are uniformly distributed across the catchment. This ignores the fact that urbanisation is likely to be not evenly distributed through out the catchment. The use of rainfall generators could help in capturing this spatial variability and deliver a more realistic risk assessment of the rainfall events that could affect the Cranbrook.

The ATP methodology should be applied to catchments of greater size and complexity to allow for better main-streaming of the methodology. The Cranbrook catchment is the largest known ATP analysis ever conducted in terms of geographical size but is still considerably smaller than a small town, or city. Further upsizing of case studies will be necessary if as a society we are to adapt to the growing risk of urban flooding.

In the future, as case studies grow in geographic size, encompass more drivers of change, and more potential strategies, there is a need to develop computational solutions to cope with growing computational demands. Due to this, there is a need to leverage the emerging power of cloud computing, parallelisation, and advances in Graphic Processor Unit design to allow for more thorough DMDU analyses to be conducted without imposing long analytical times.

The current methodology of manually setting up simulations to run in groups is at its practical limit. In order to explore more drivers and strategies efficiently tools to interface with Infoworks ICM's Application Programming Interface (API) will need to be developed. This would result the ability to set up simulations much more much quickly with easier extraction of results and more efficient work processes.

The costs and benefits of the Adaptation Pathways could be re-evaluated using alternative methods. Costs could be estimated through the use of more detailed designs, thereby allowing for a better assessment of costs. Furthermore, flood damage estimation methods that take into account the heightened property values of London would more allow for a more accurate reflection of flood risk benefits than the ones calculated earlier which were calculated based on averaged UK data.

The comparison of different sets of Adaptation Pathways was completed in a qualitative manner. There is the potential to develop a method to compare different sets of Adaptation Pathways to one another. Quantitative comparisons between sets of Adaptation Pathways are difficult to undertake due to pathways being developed for different drivers of change, different solutions being presented in different pathways, and adaptations may be implemented in different orders. A method for identifying the similarity between pathways would be of great scientific and practical use for the DMDU community.

Within this thesis the effects of climate change were applied to a drainage system in isolation. Much of water resource management is moving towards an integrated framework. As models and management paradigms becoming increasingly integrated Adaptation Tipping Points should be applied to such models. A DMDU investigation of both water resources and flooding infrastructure would represent a quantum leap in developing urban water planning and adaptations.

Appendix A

Adaptation Maps

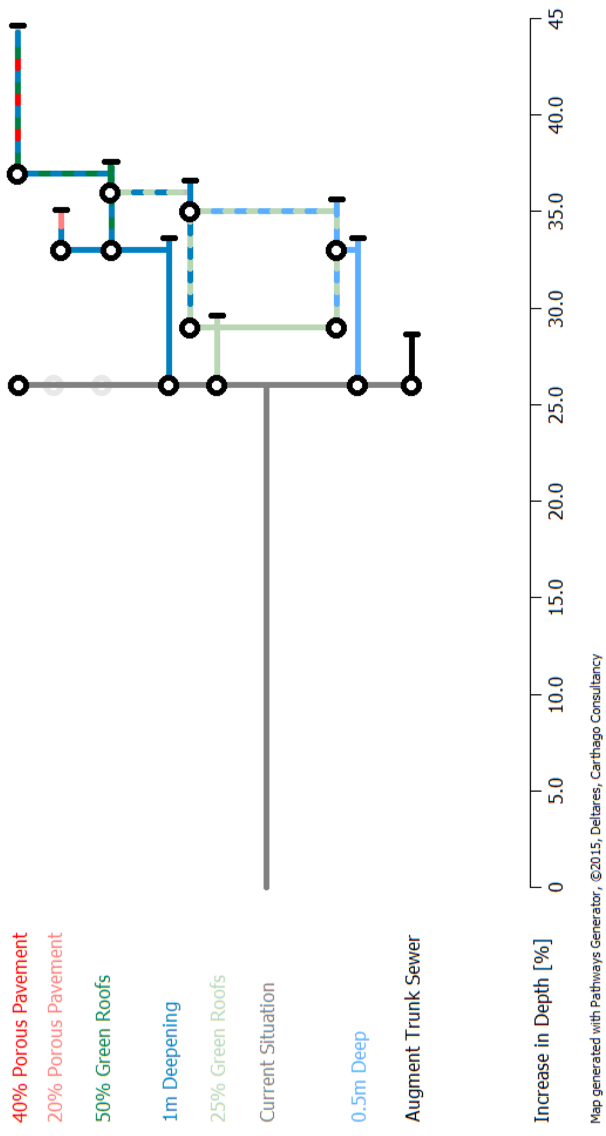


Figure A.1: Adaptation Map for Increasing Storm Depth and Peakedness of 3.0

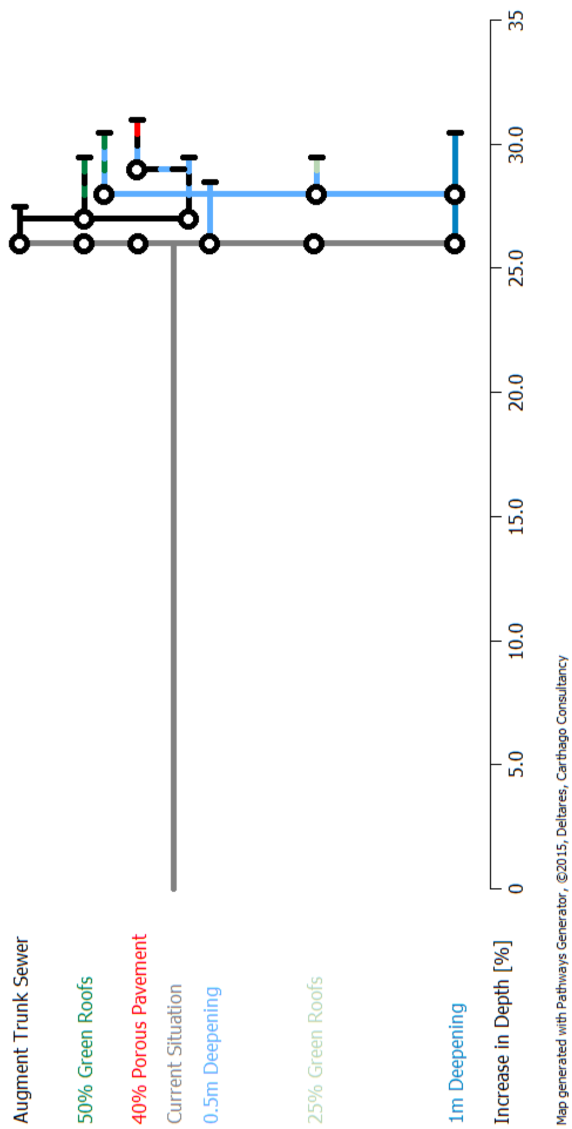


Figure A.2: Adaptation Map for Increasing Storm Depth and Peakedness of 3.3

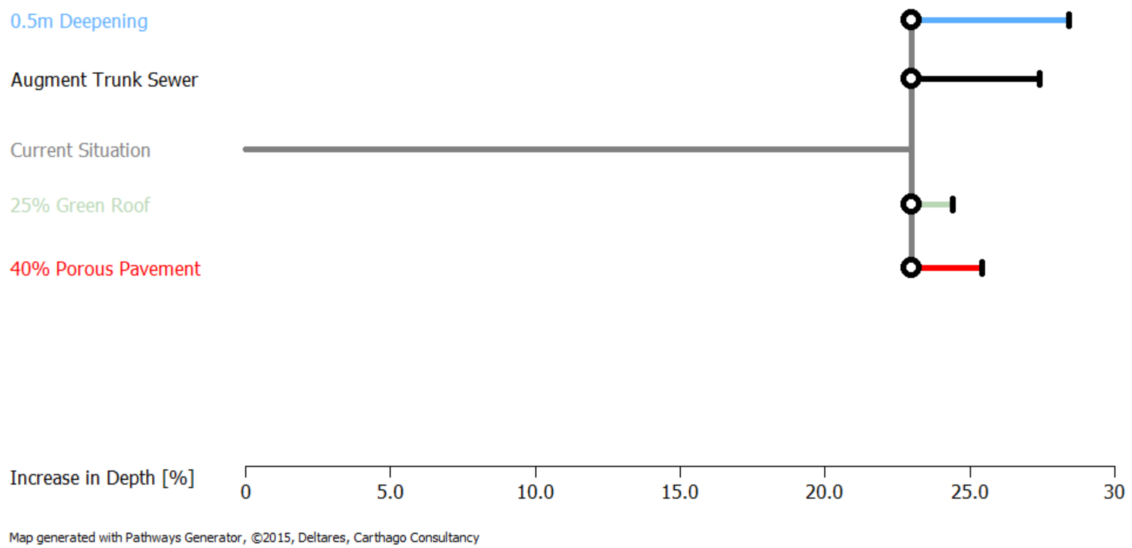


Figure A.3: Adaptation Map for Increasing Storm Depth and Peakedness of 3.6

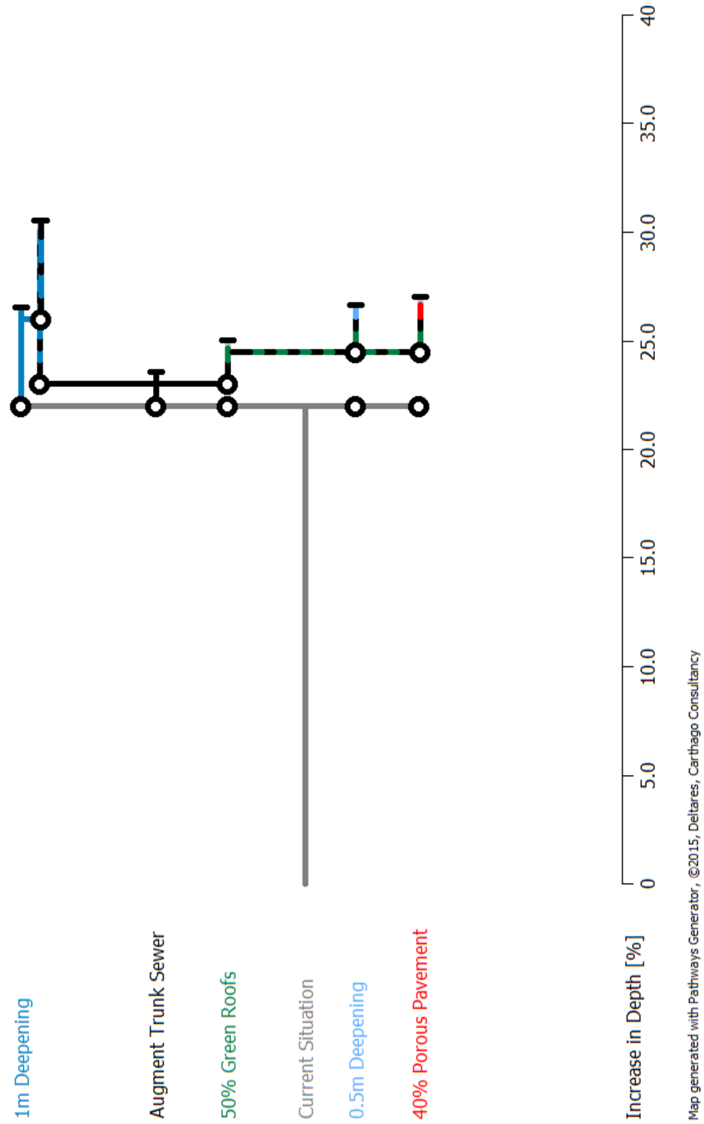


Figure A.4: Adaptation Map for Increasing Storm Depth and Peakedness of 3.9

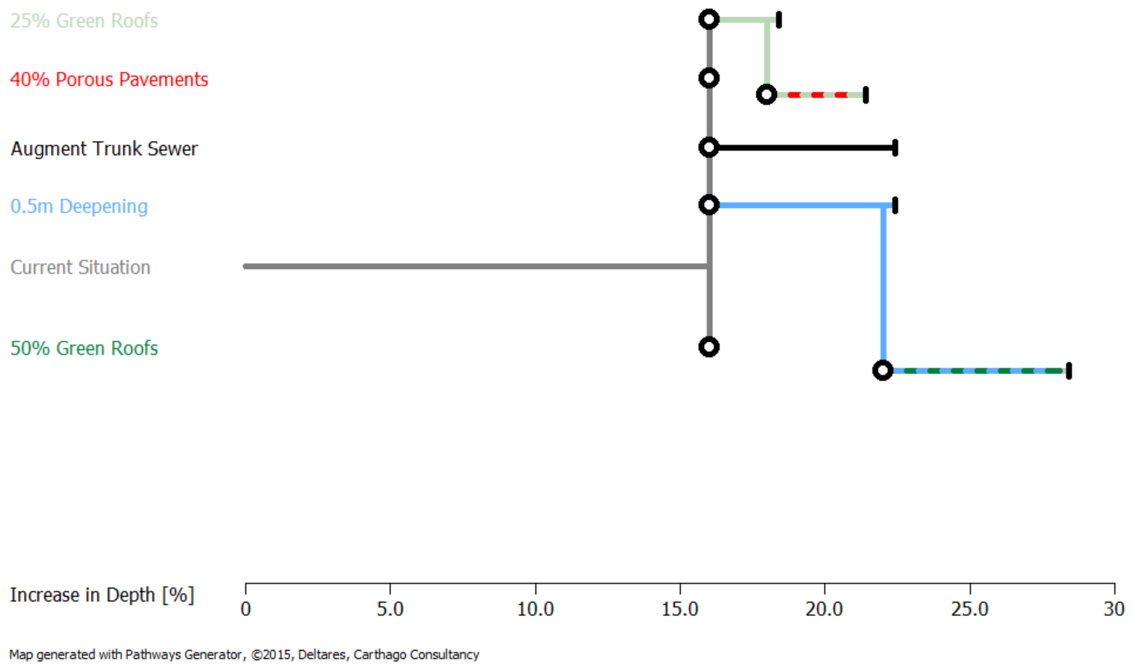


Figure A.5: Adaptation Map for Increasing Storm Depth and Peakedness of 4.2

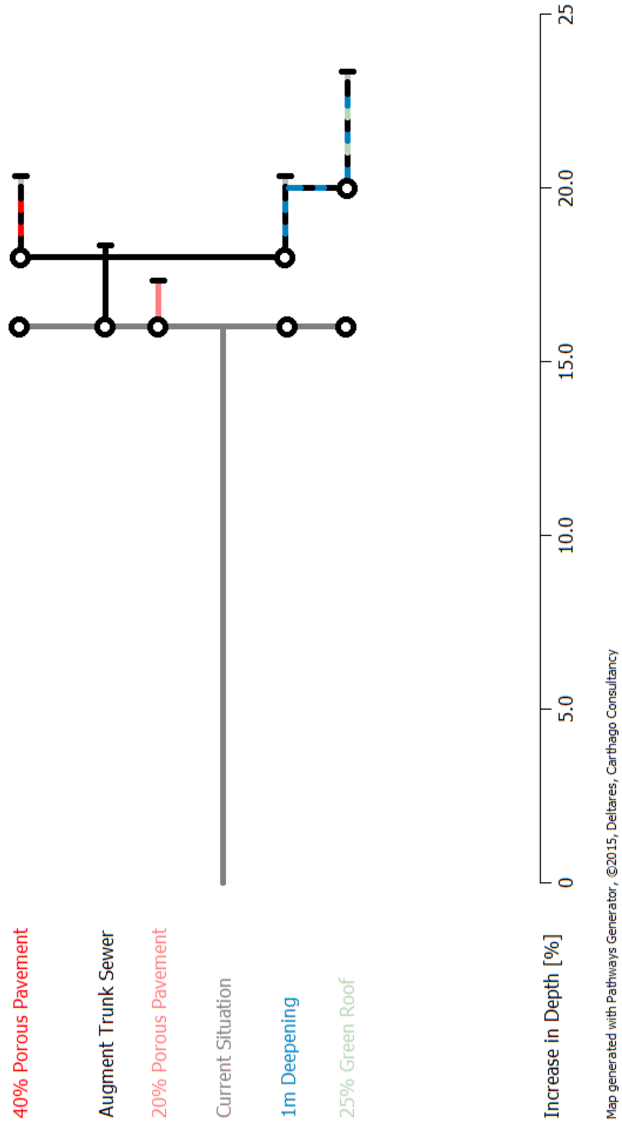


Figure A.6: Adaptation Map for Increasing Storm Depth and Peakedness of 4.5

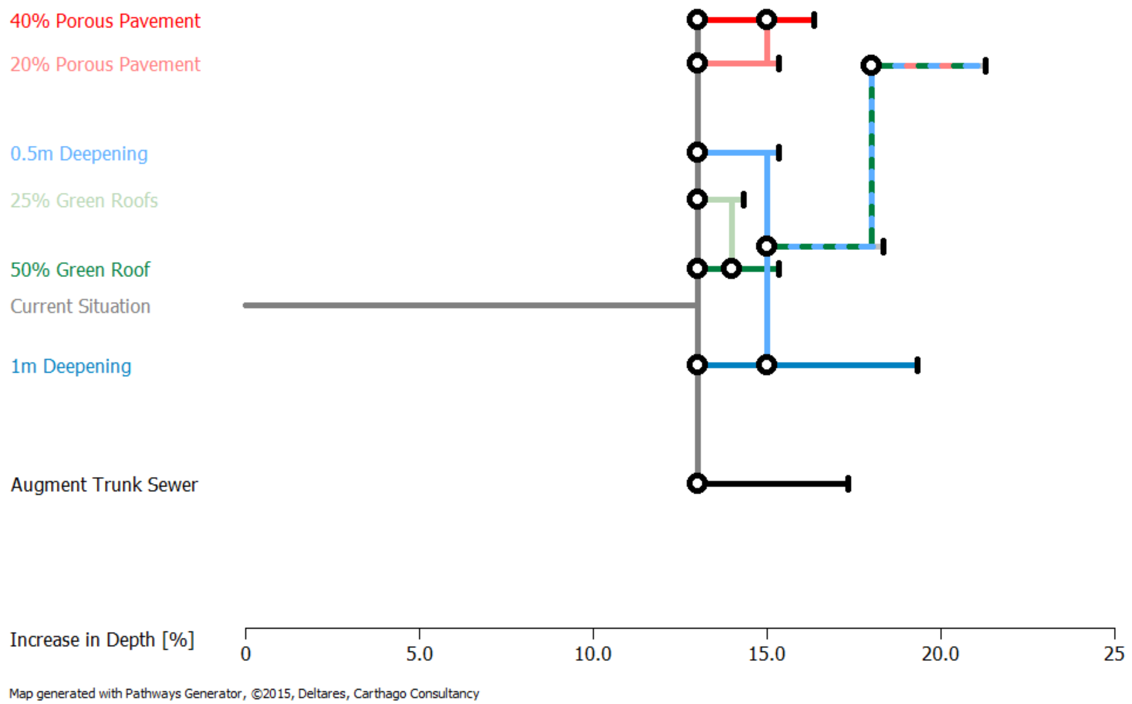


Figure A.7: Adaptation Map for Increasing Storm Depth and Peakedness of 4.8

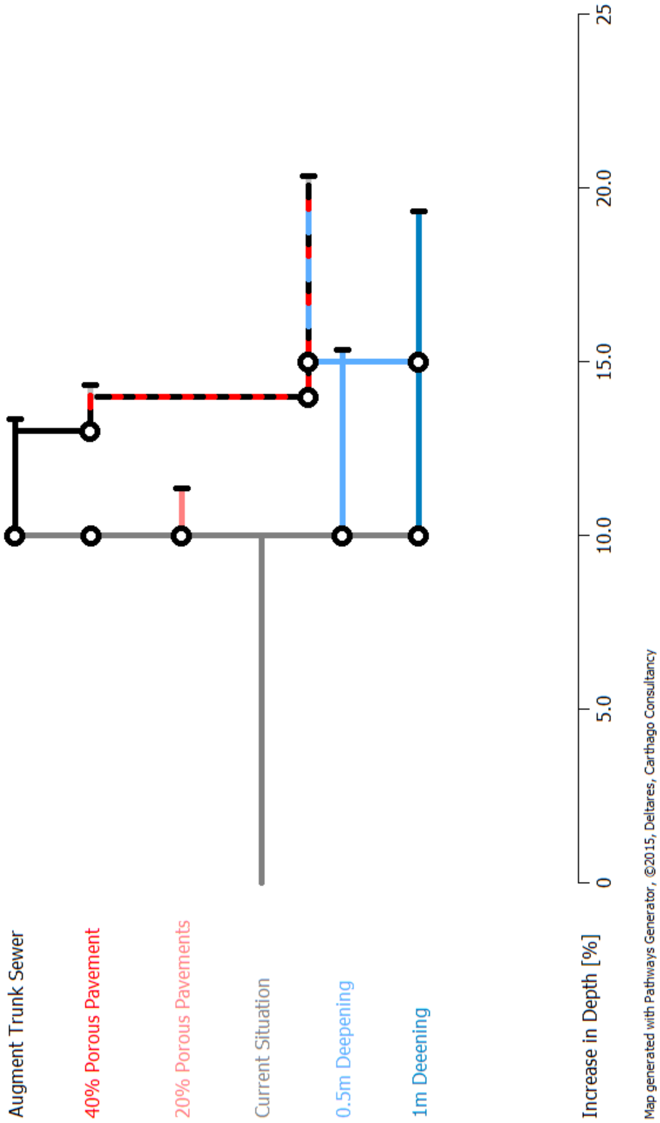


Figure A.8: Adaptation Map for Increasing Storm Depth and Peakedness of 5.1

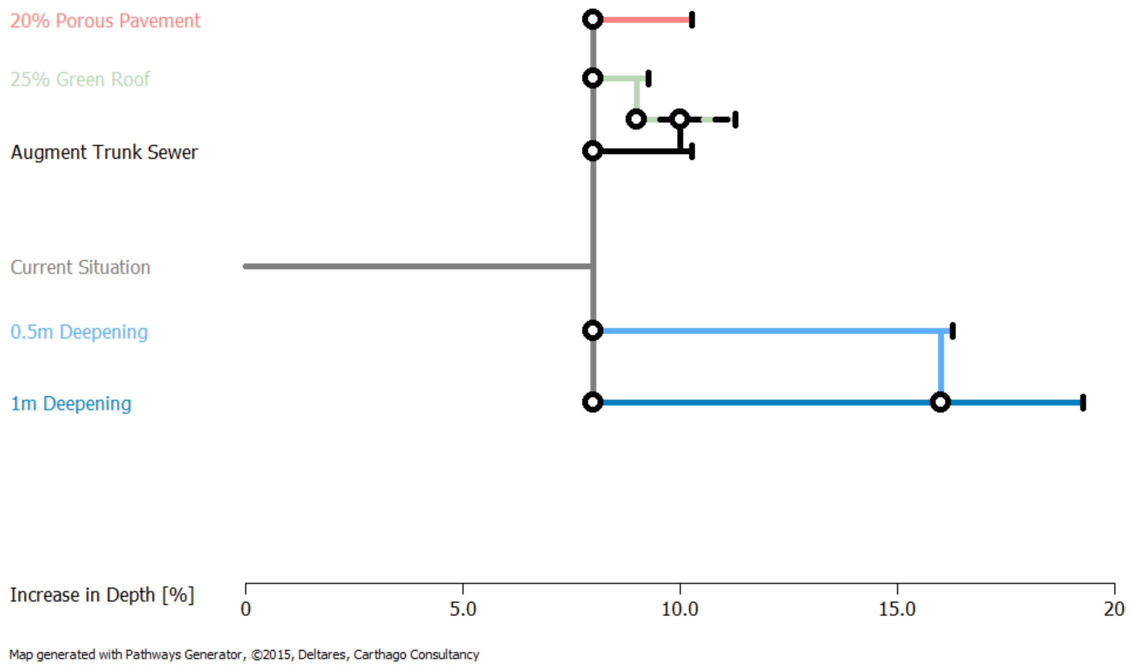


Figure A.9: Adaptation Map for Increasing Storm Depth and Peakedness of 5.4

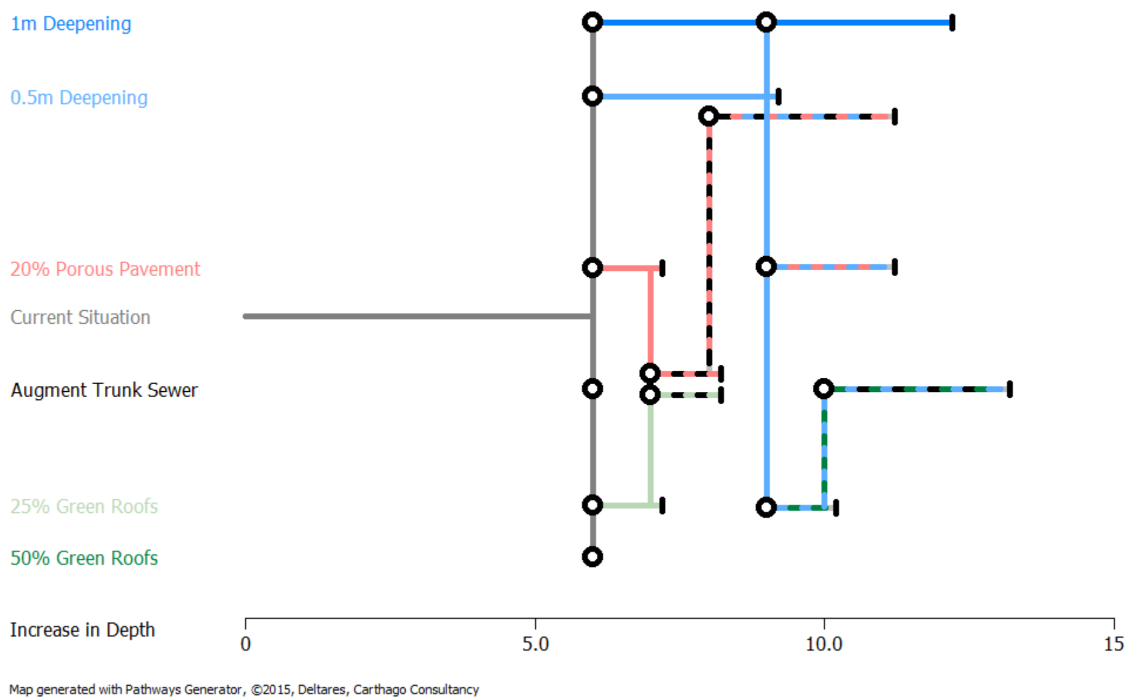


Figure A.10: Adaptation Map for Increasing Storm Depth and Peakedness of 5.7

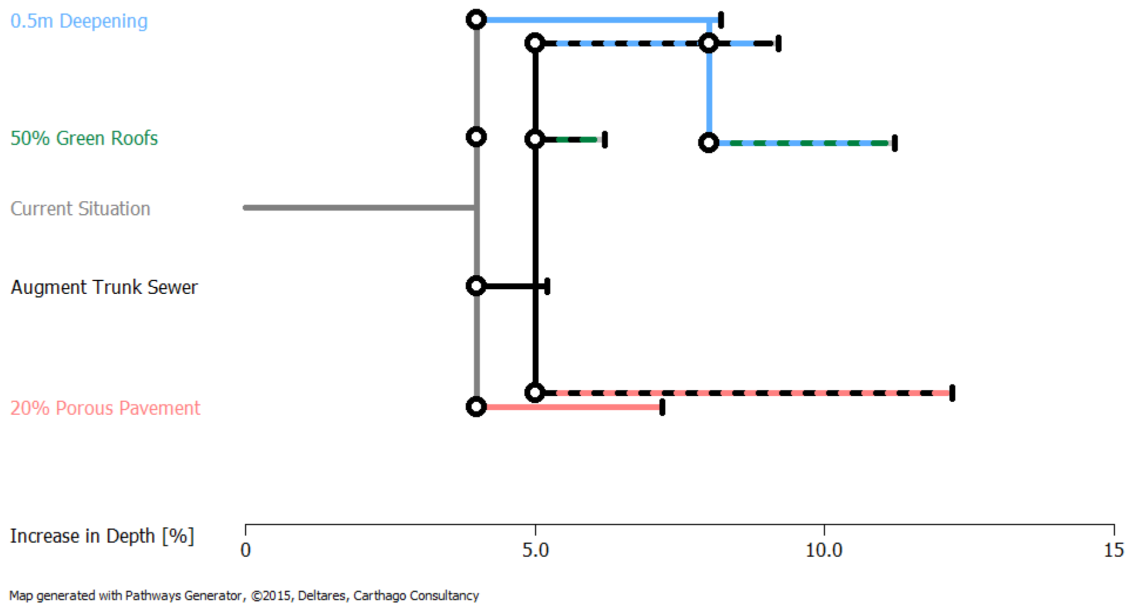


Figure A.11: Adaptation Map for Increasing Storm Depth and Peakedness of 6.0

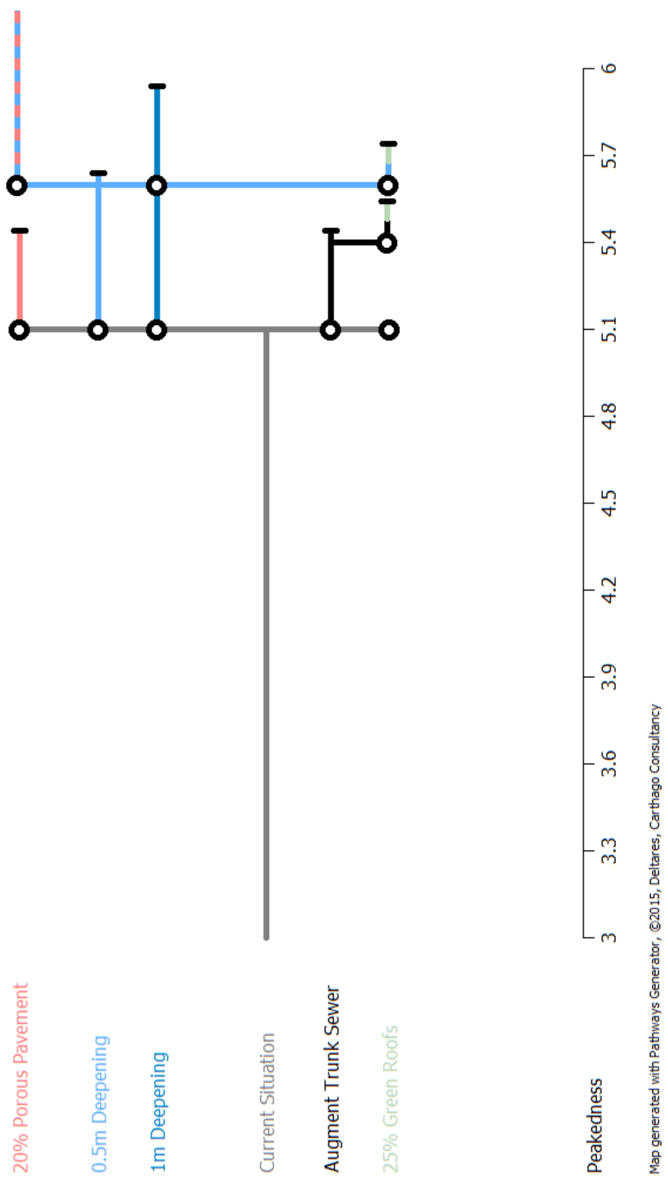


Figure A.12: Adaptation Map for Increasing Storm Peakedness and Increase in Depth of 10%

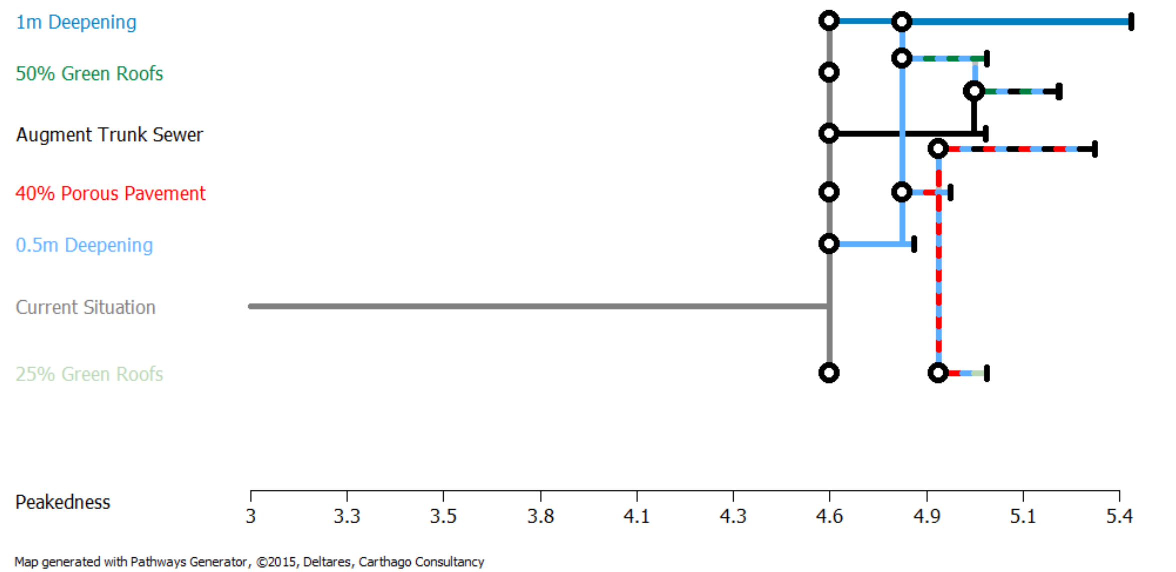


Figure A.13: Adaptation Map for Increasing Storm Peakedness and Increase in Depth of 15%

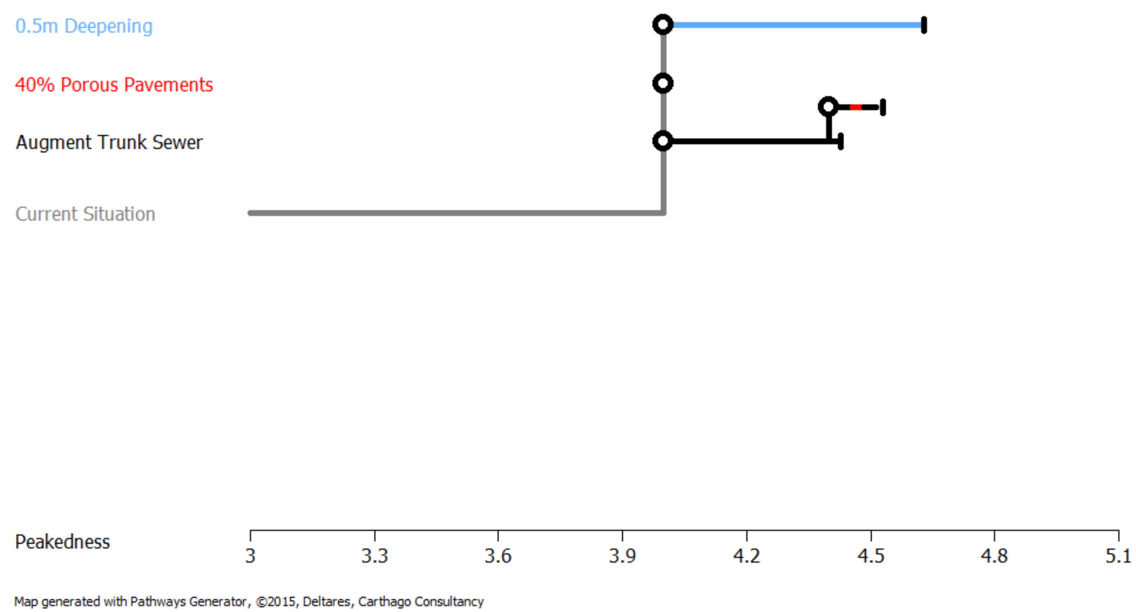


Figure A.14: Adaptation Map for Increasing Storm Peakedness and Increase in Depth of 20%

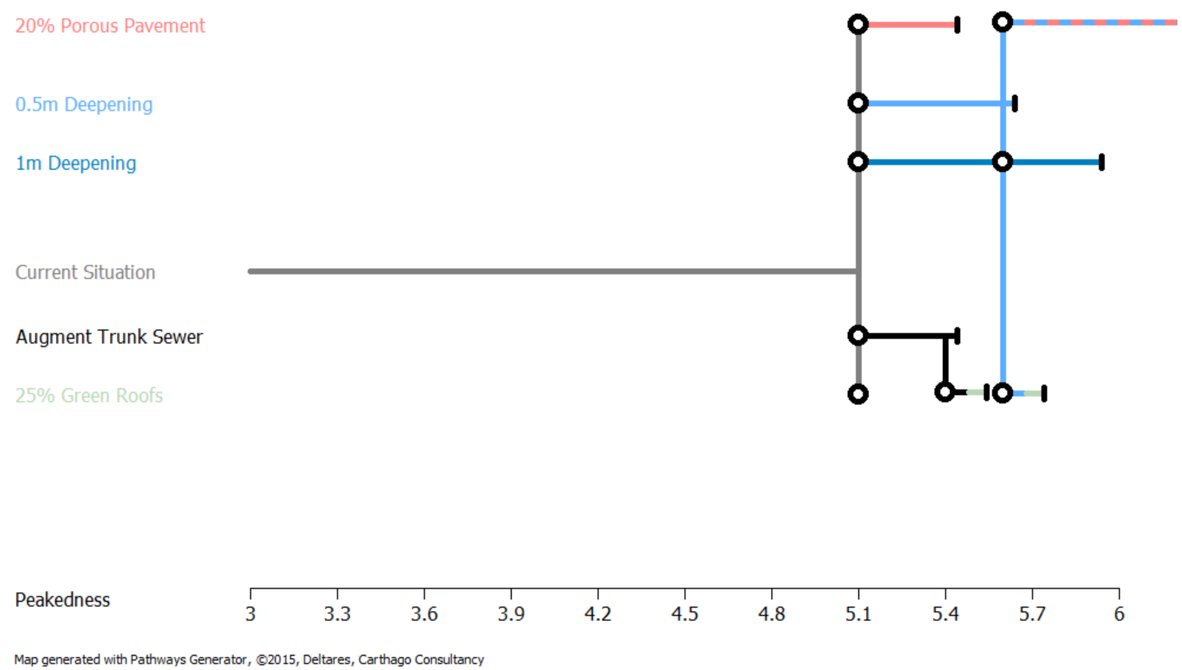


Figure A.15: Adaptation Map for Increasing Storm Peakedness and Increase in Depth of 25%

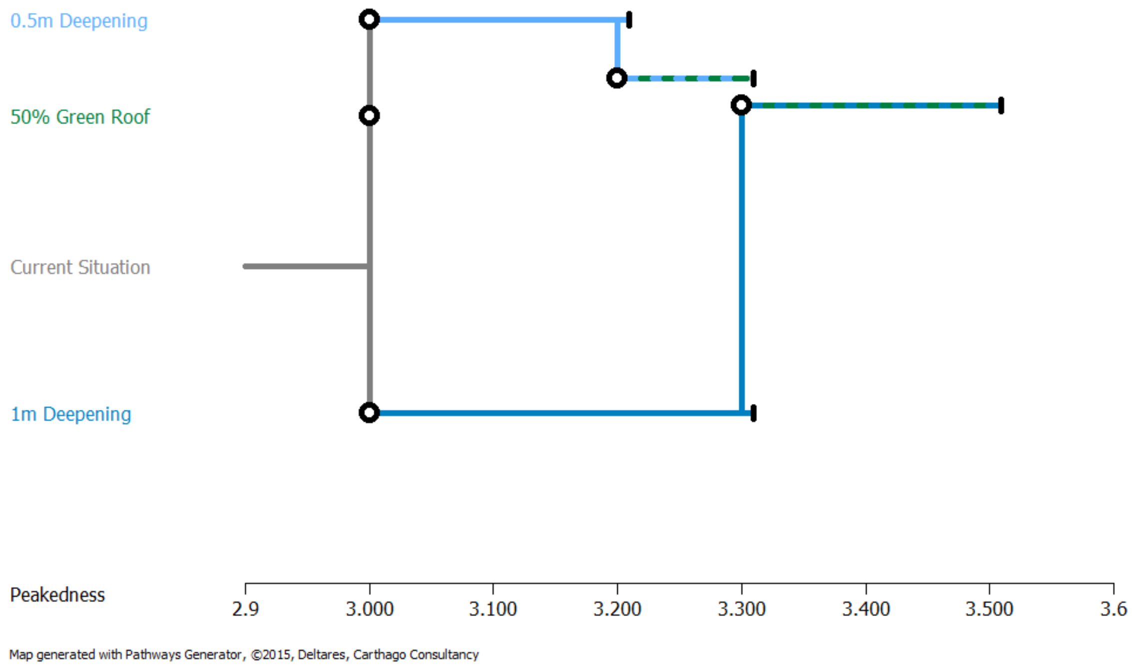


Figure A.16: Adaptation Map for Increasing Storm Peakedness and Increase in Depth of 30%

Appendix B

Empirical Cumulative Distribution Functions of Financial Performance under Uncertainty

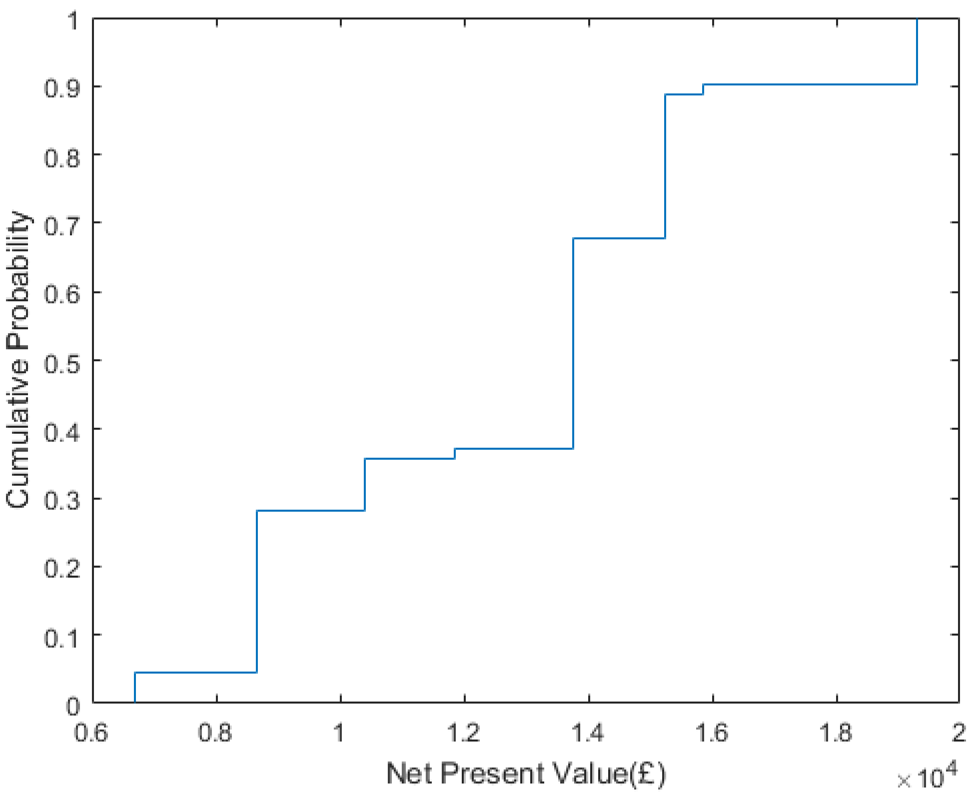


Figure B.1: Empirical Cumulative Distribution of NPV for Path A

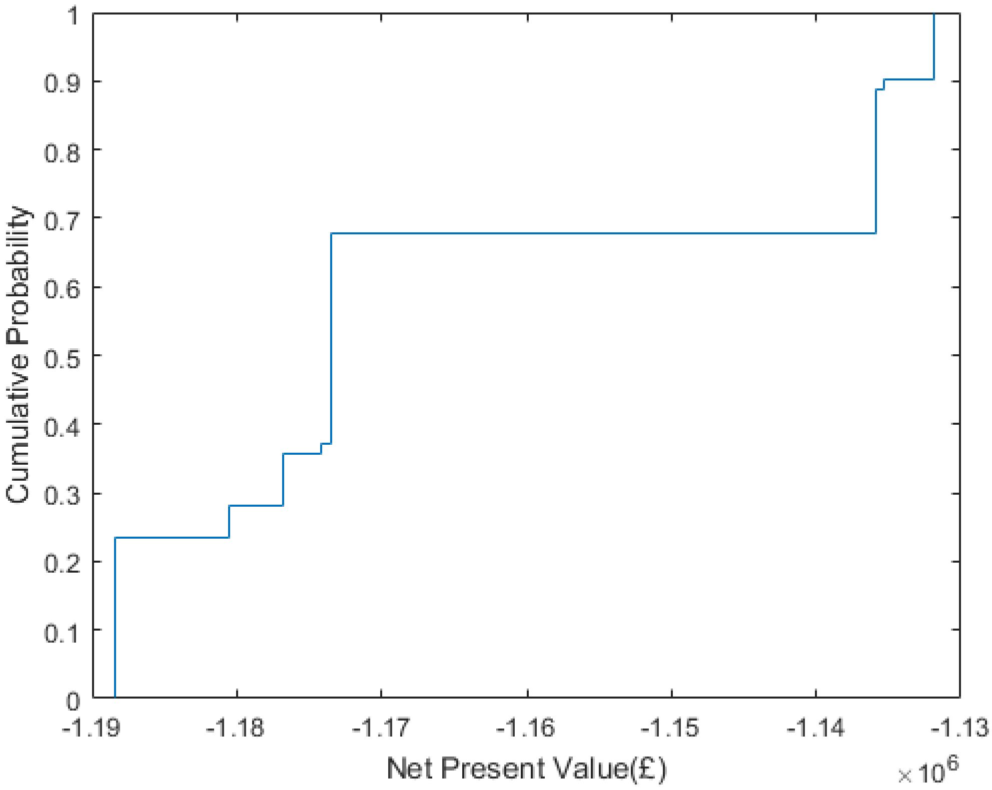


Figure B.2: Empirical Cumulative Distribution of NPV for Path B

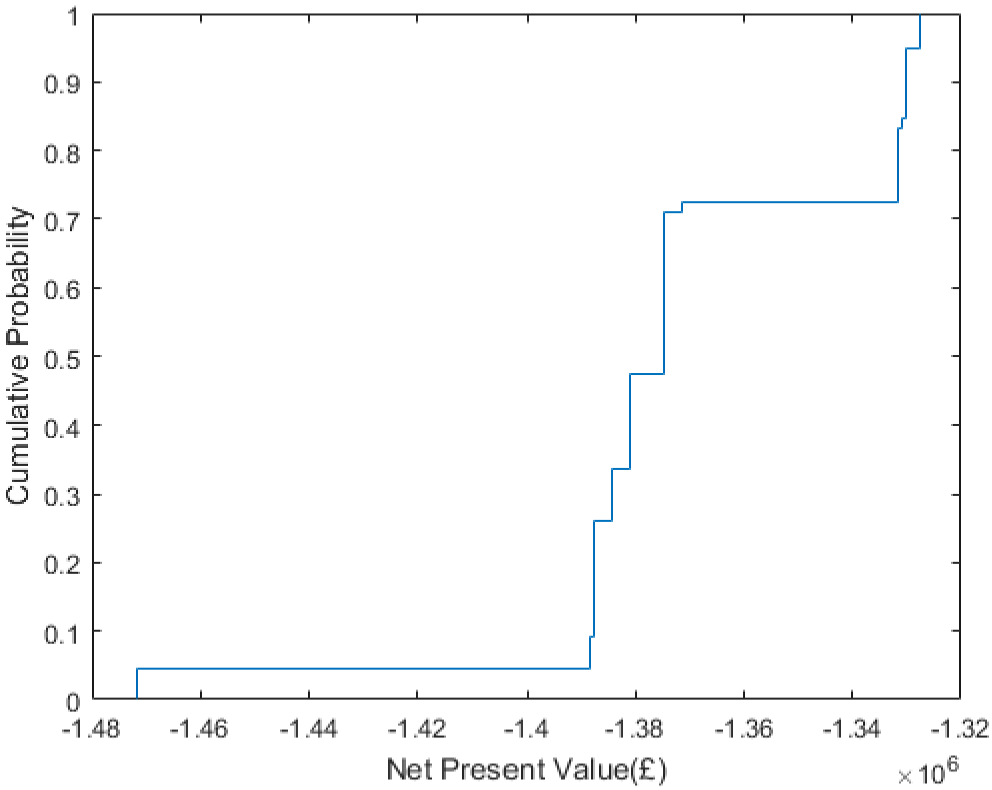


Figure B.3: Empirical Cumulative Distribution of NPV for Path C

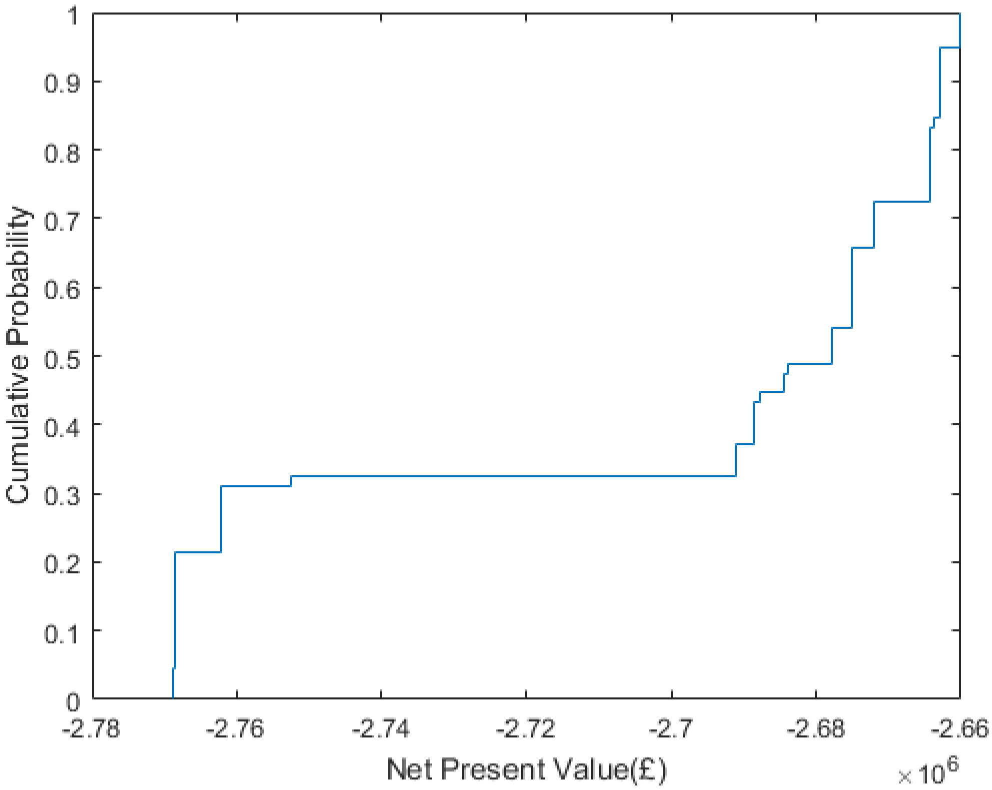


Figure B.4: Empirical Cumulative Distribution of NPV for Path D

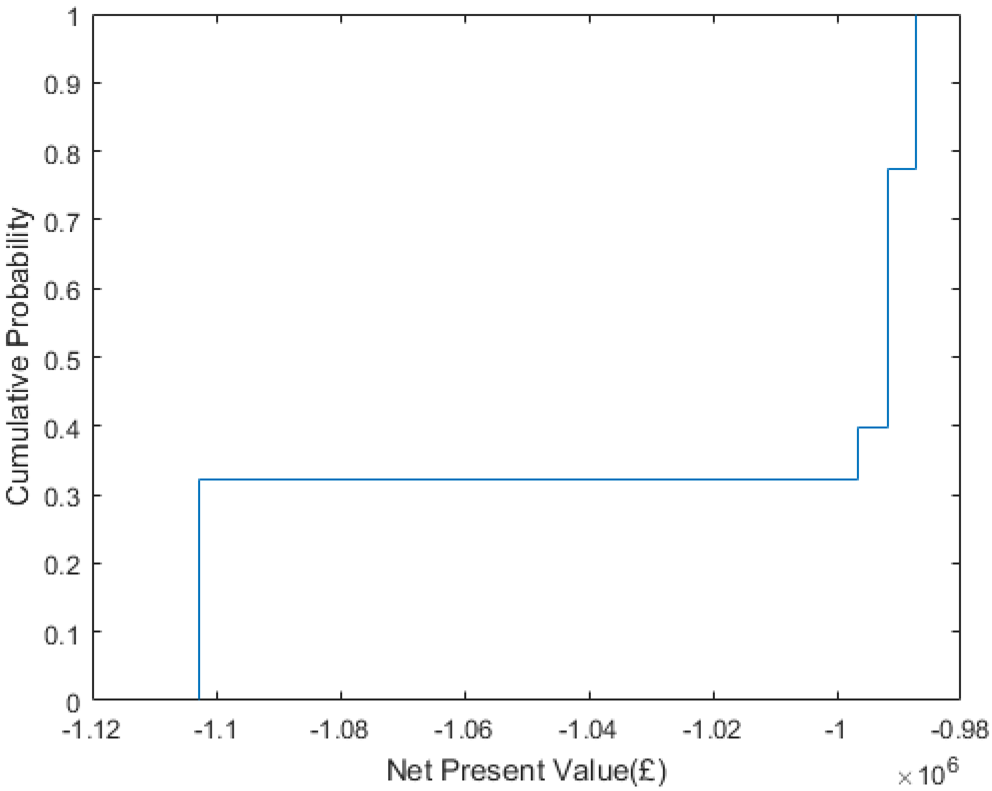


Figure B.5: Empirical Cumulative Distribution of NPV for Path E

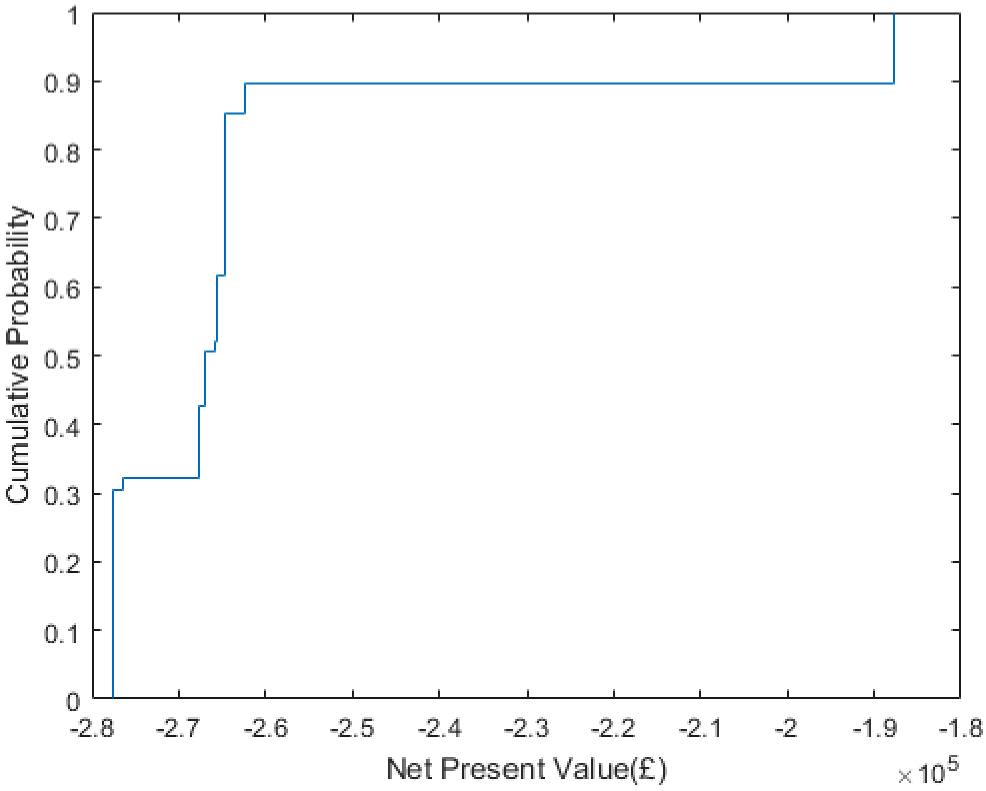


Figure B.6: Empirical Cumulative Distribution of NPV for Path F

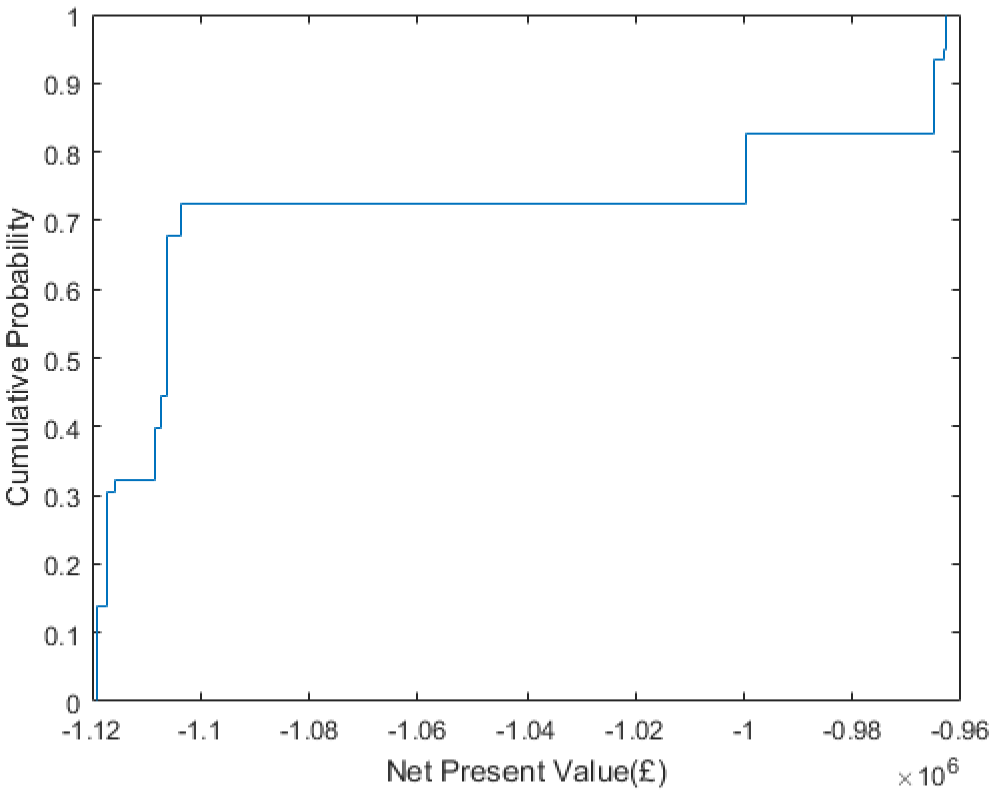


Figure B.7: Empirical Cumulative Distribution of NPV for Path G

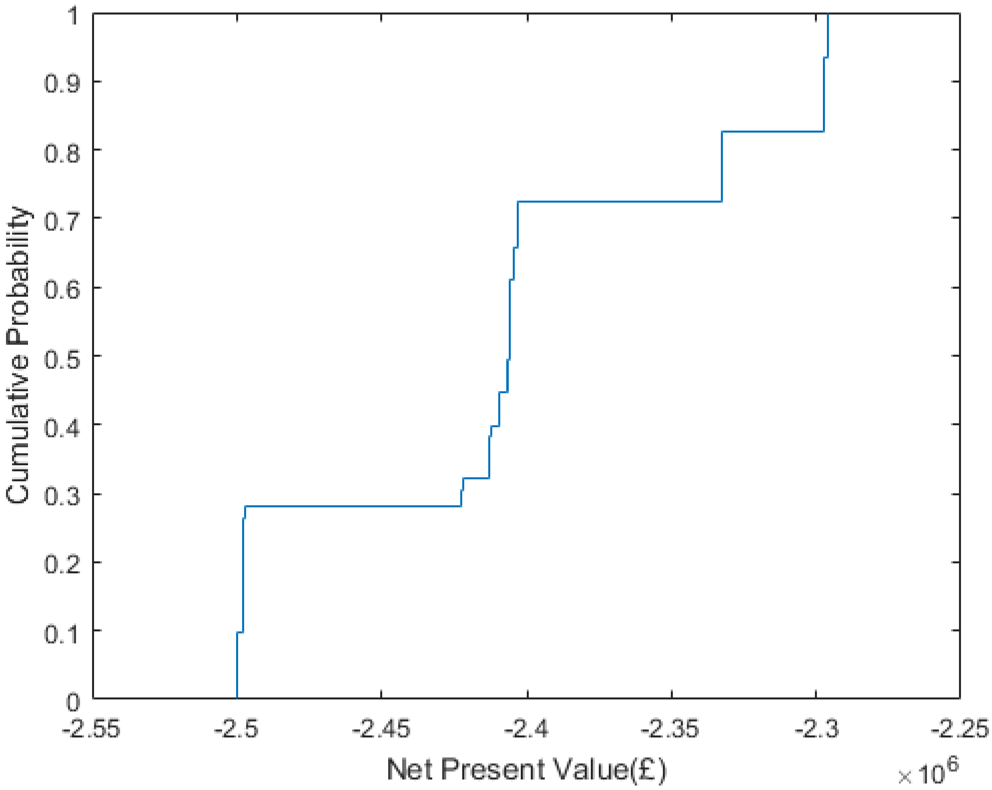


Figure B.8: Empirical Cumulative Distribution of NPV for Path H

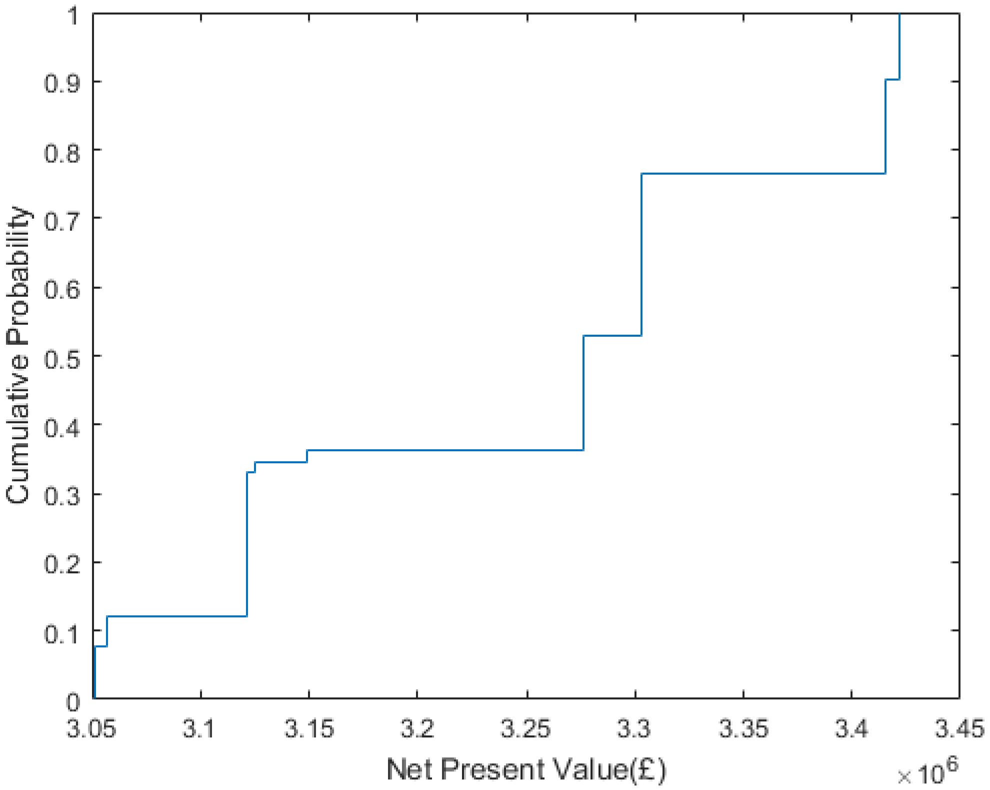


Figure B.9: Empirical Cumulative Distribution of NPV for Path I

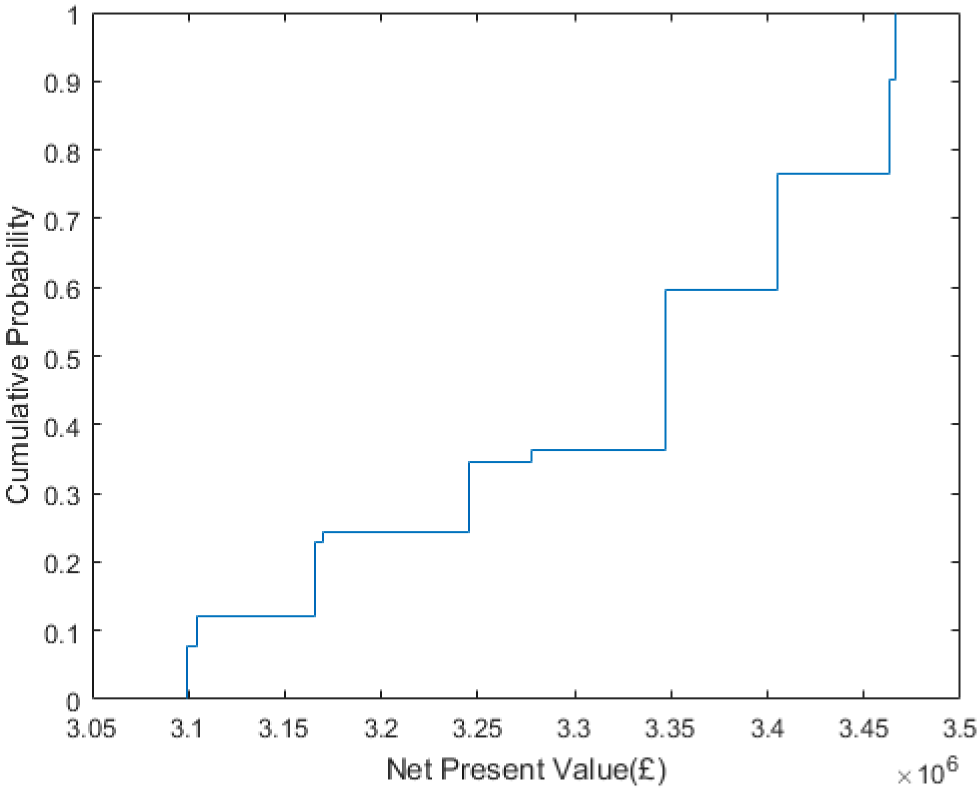


Figure B.10: Empirical Cumulative Distribution of NPV for Path J

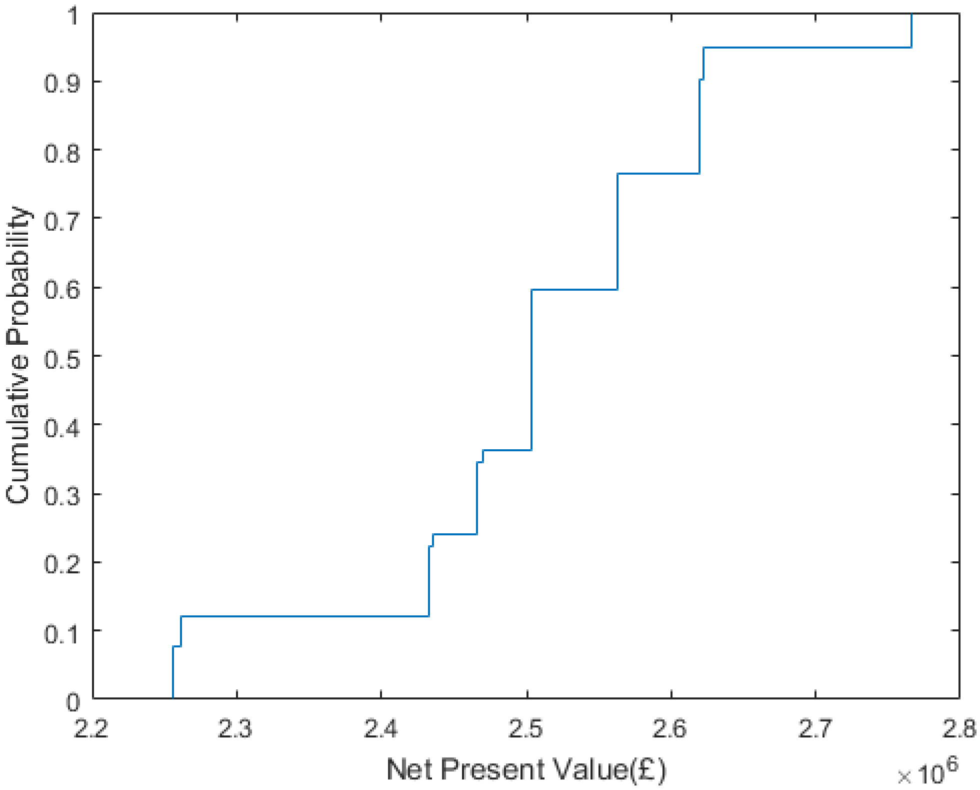


Figure B.11: Empirical Cumulative Distribution of NPV for Path K

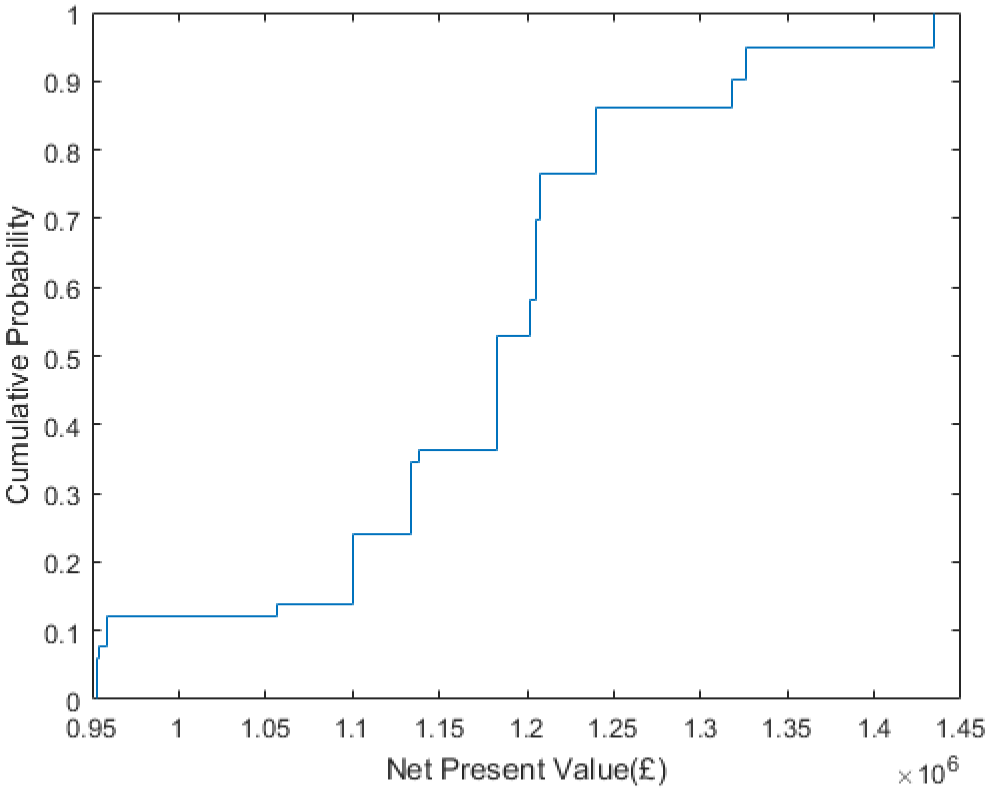


Figure B.12: Empirical Cumulative Distribution of NPV for Path L

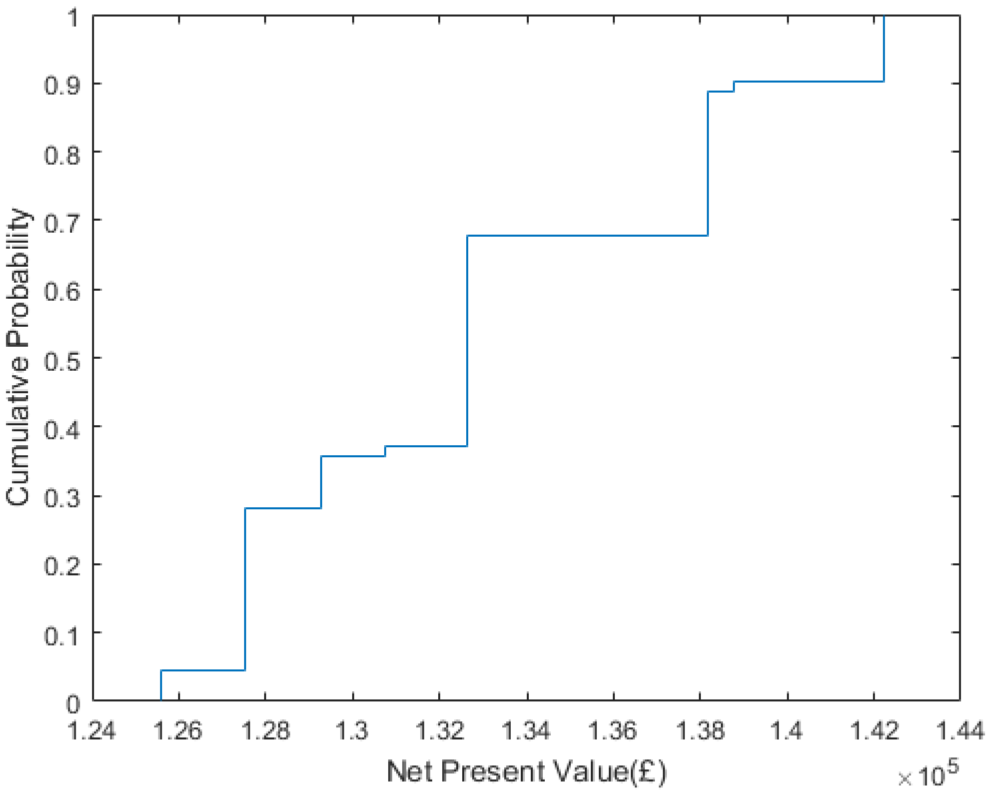


Figure B.13: Empirical Cumulative Distribution of NPV for Path M

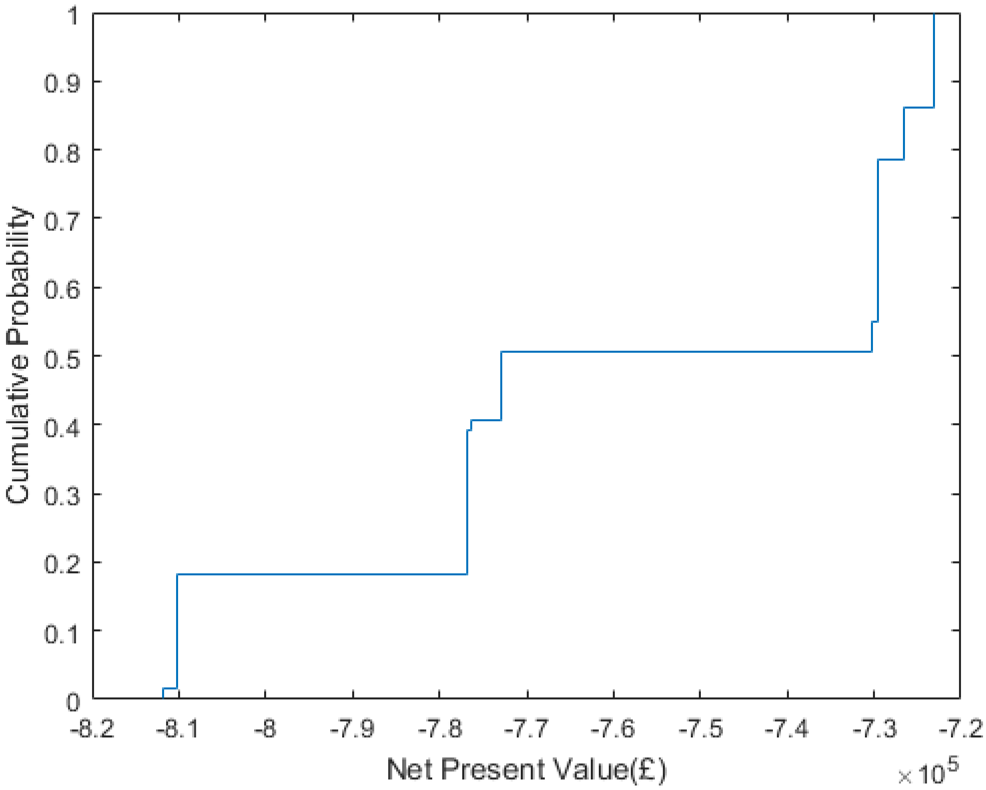


Figure B.14: Empirical Cumulative Distribution of NPV for Path N

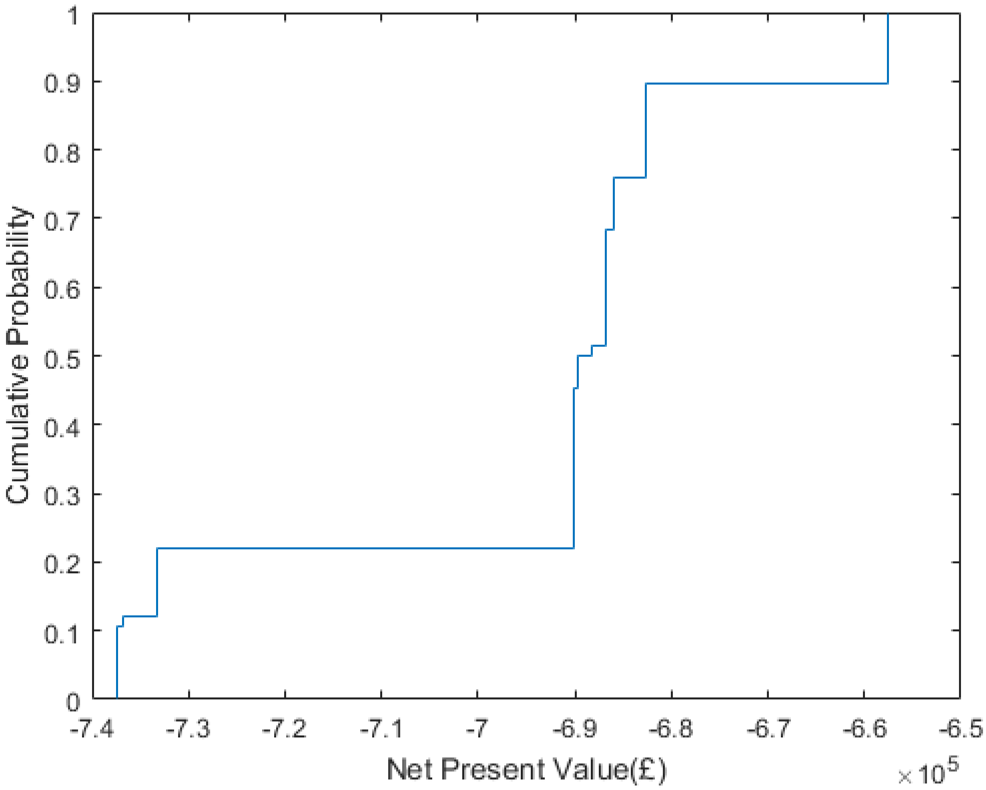


Figure B.15: Empirical Cumulative Distribution of NPV for Path O

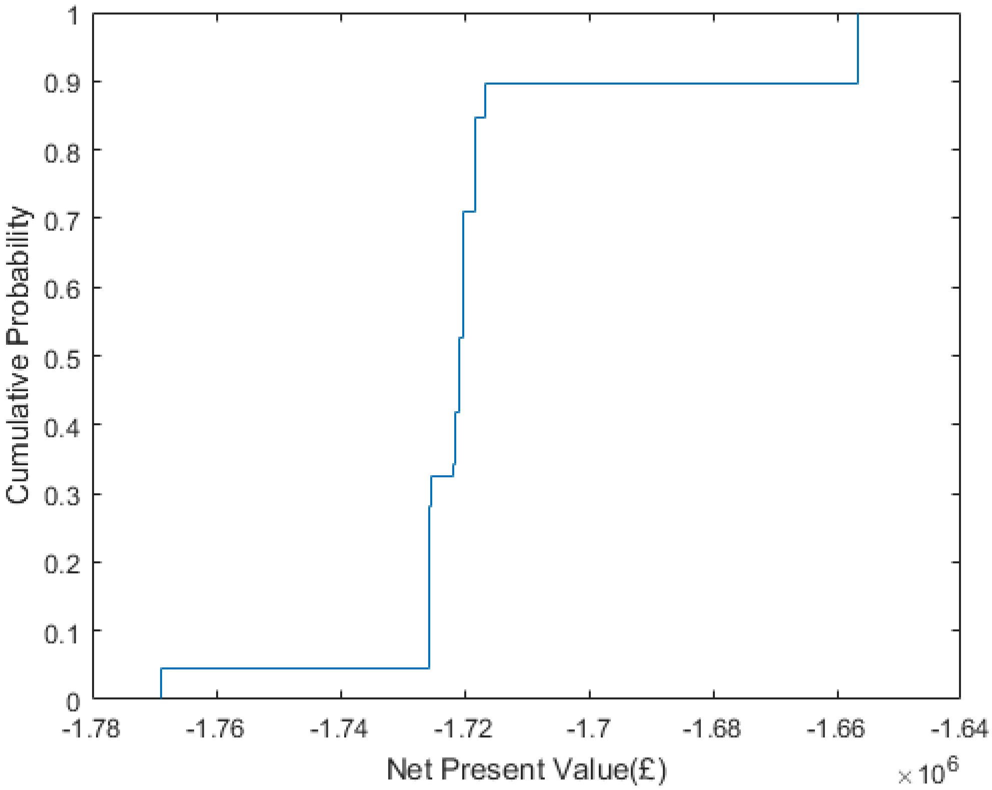


Figure B.16: Empirical Cumulative Distribution of NPV for Path P

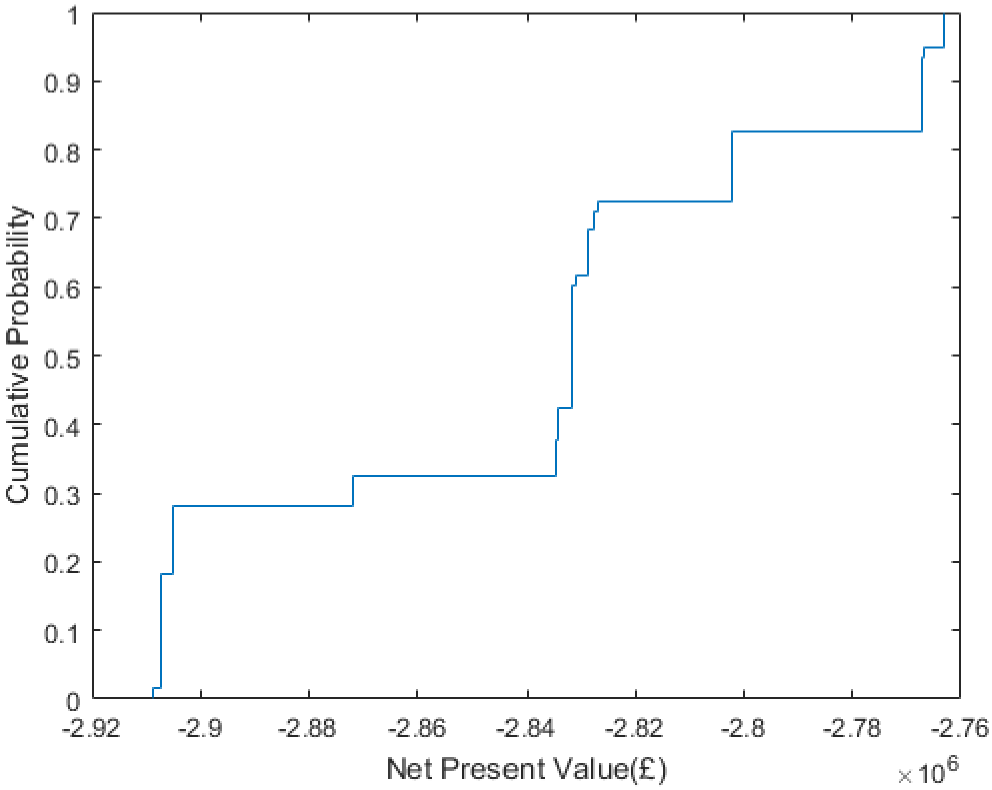


Figure B.17: Empirical Cumulative Distribution of NPV for Path Q

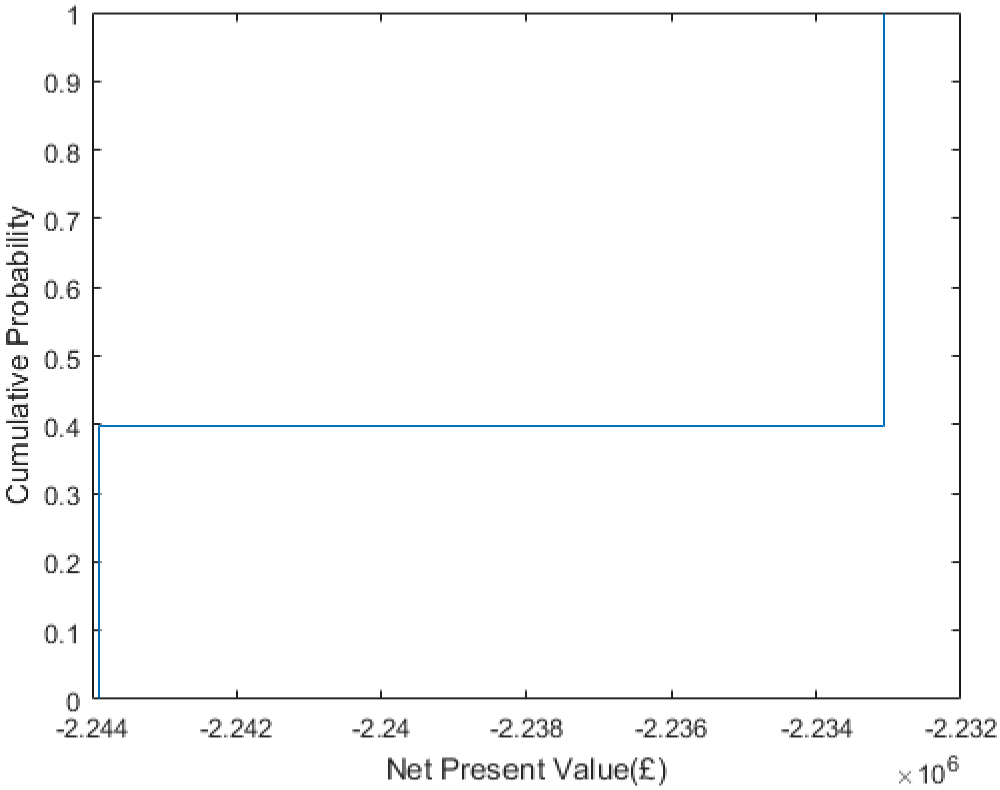


Figure B.18: Empirical Cumulative Distribution of NPV for Path R

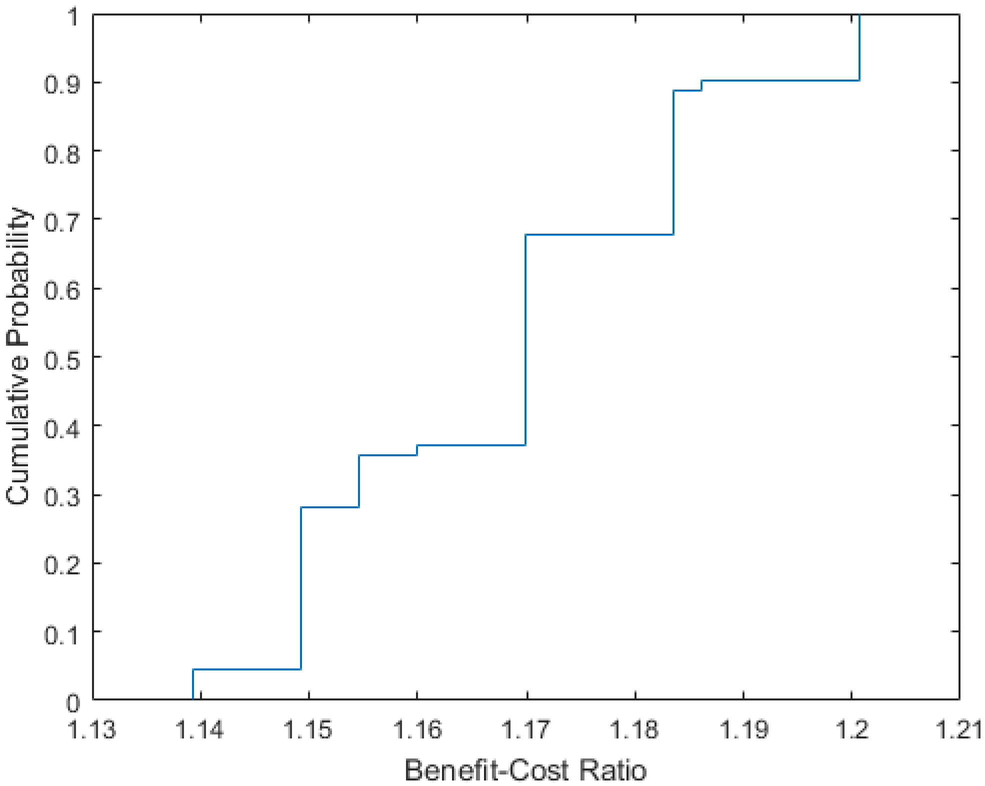


Figure B.19: Empirical Cumulative Distribution of BCR for Path A

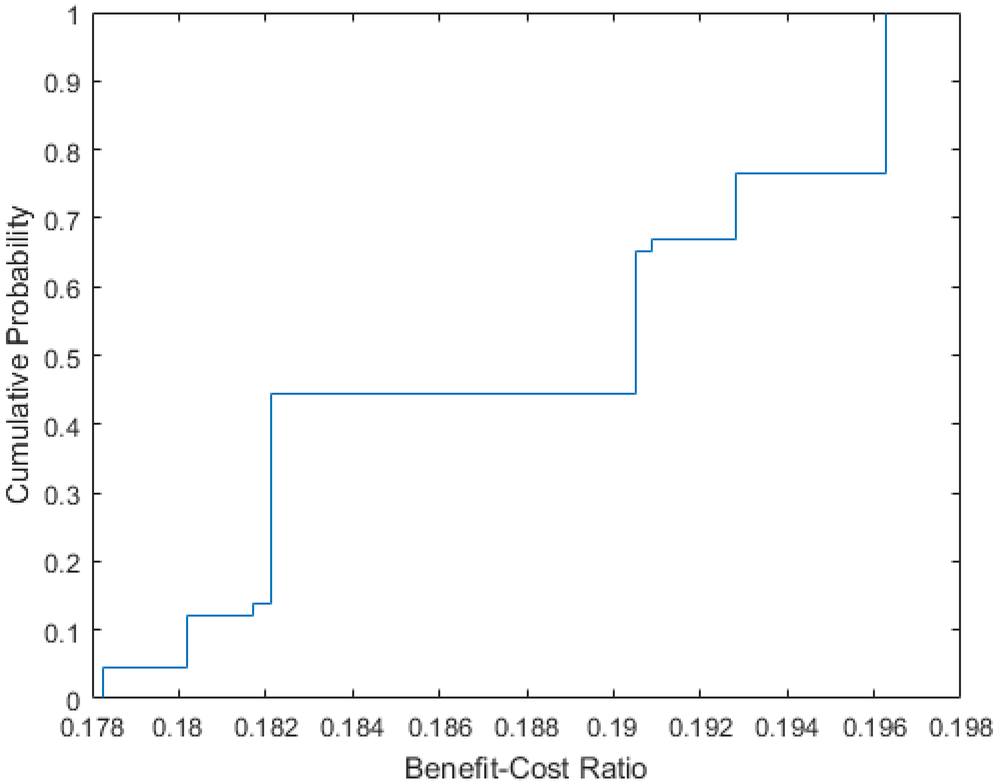


Figure B.20: Empirical Cumulative Distribution of BCR for Path B

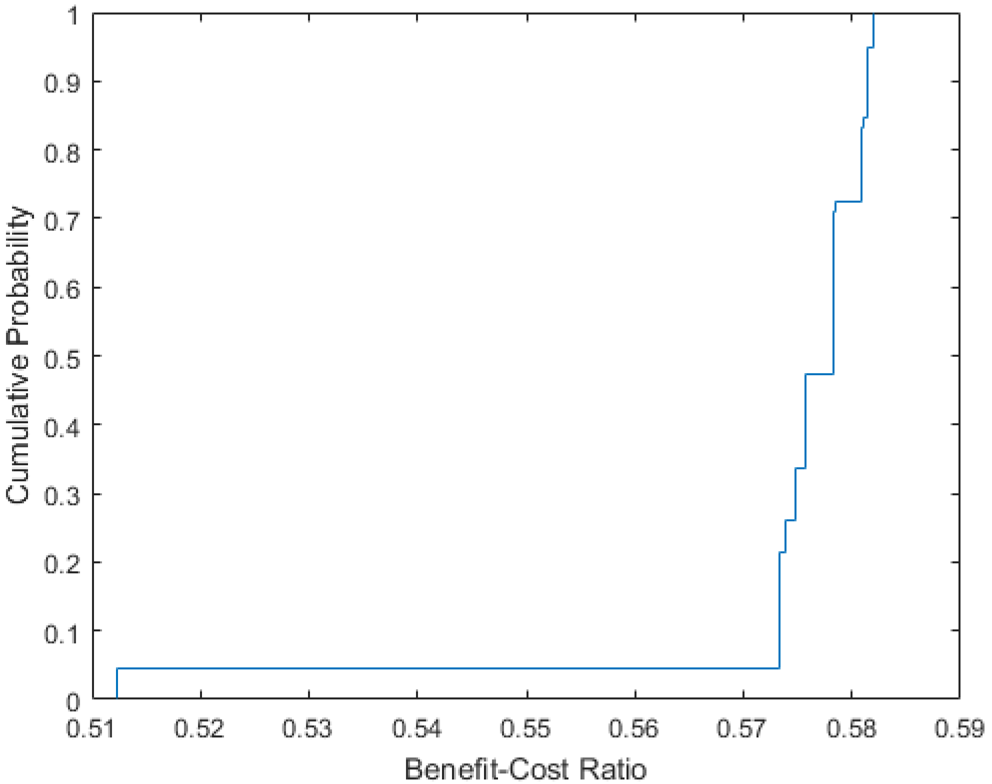


Figure B.21: Empirical Cumulative Distribution of BCR for Path C

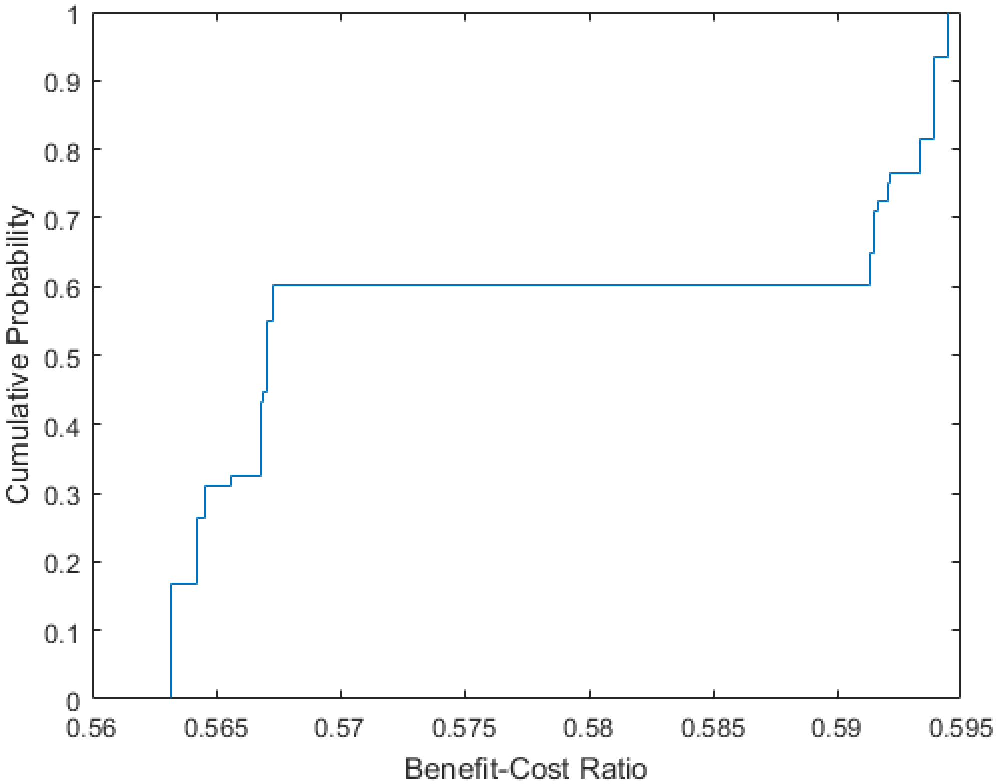


Figure B.22: Empirical Cumulative Distribution of BCR for Path D

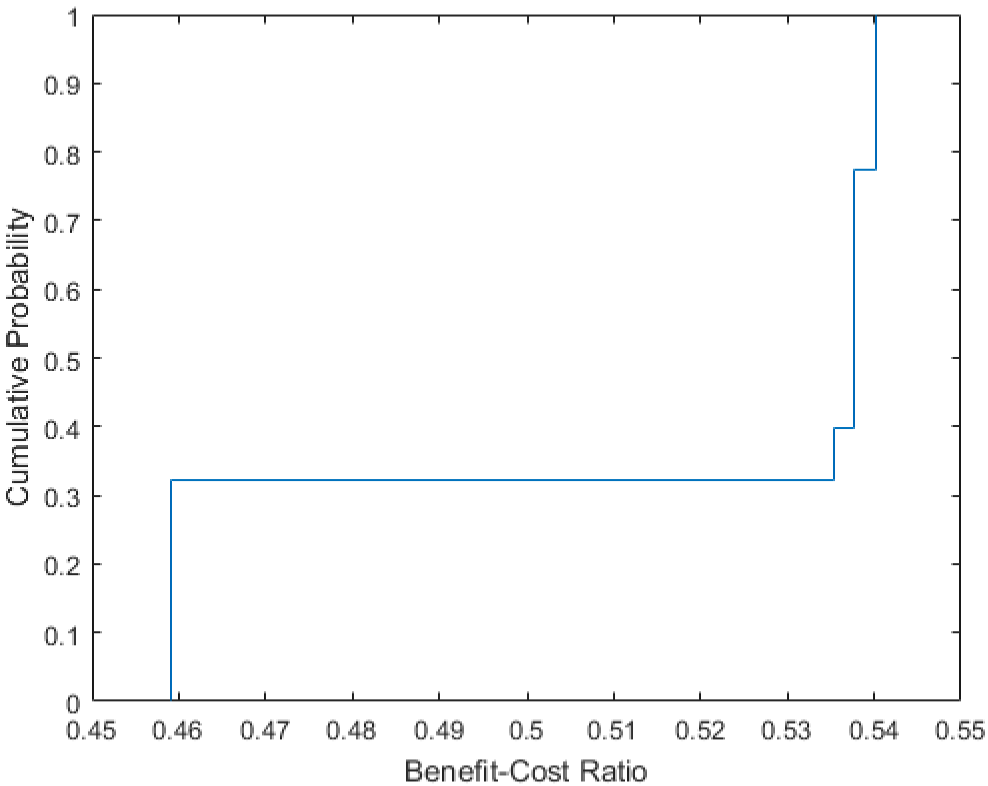


Figure B.23: Empirical Cumulative Distribution of BCR for Path E

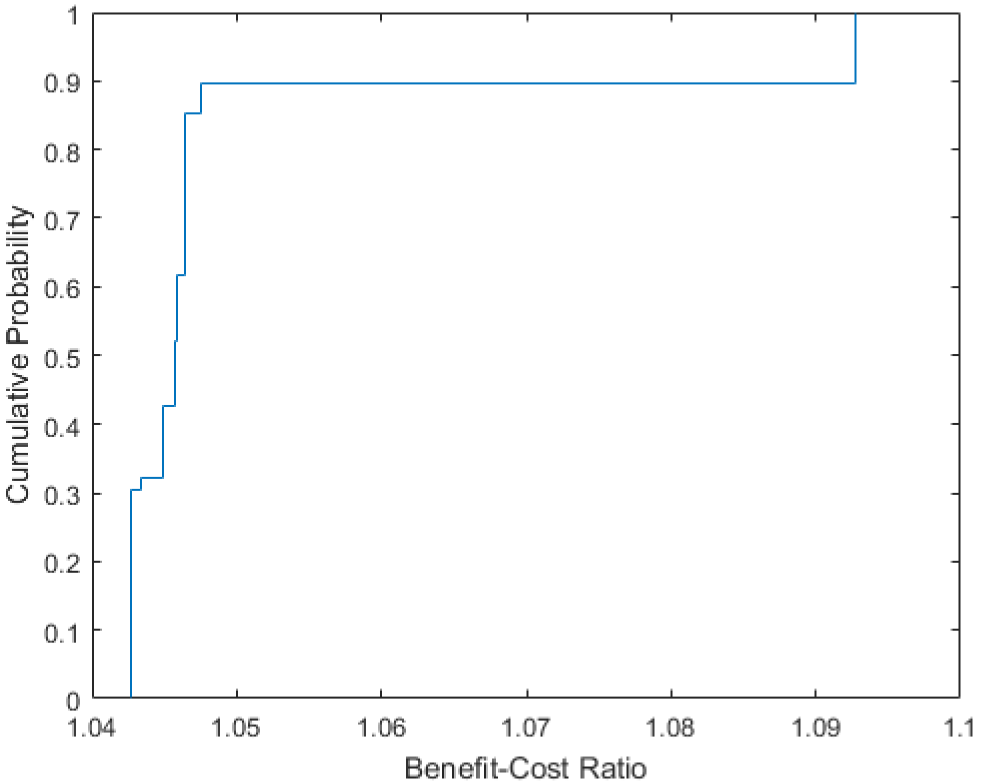


Figure B.24: Empirical Cumulative Distribution of BCR for Path F

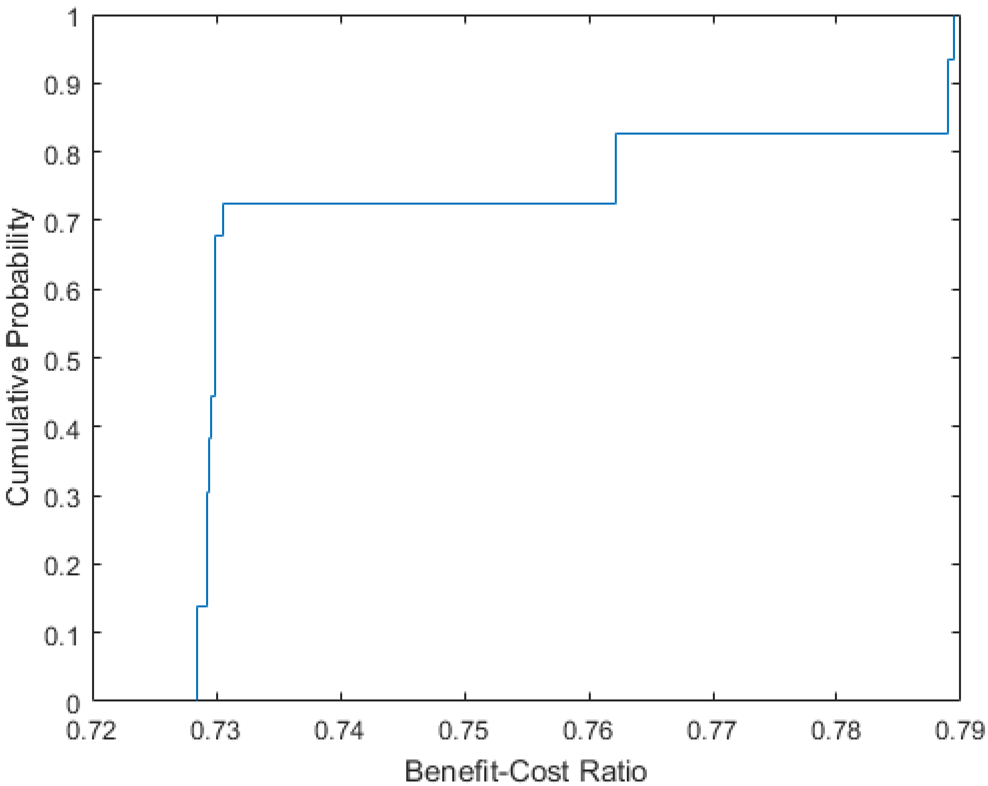


Figure B.25: Empirical Cumulative Distribution of BCR for Path G

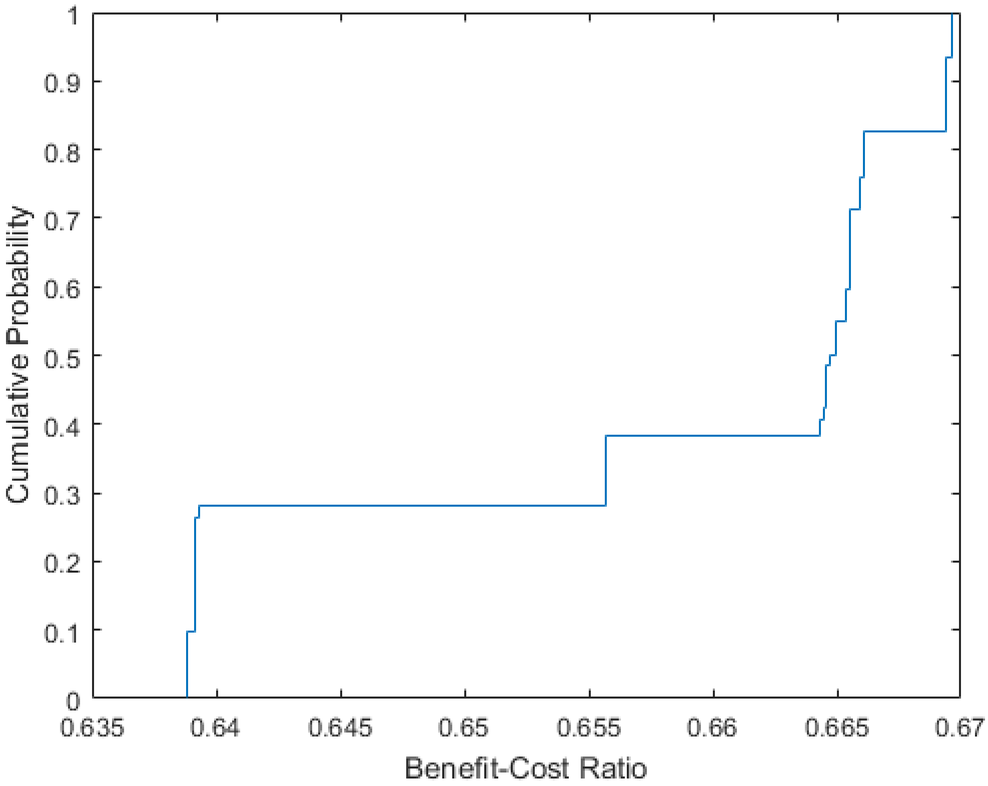


Figure B.26: Empirical Cumulative Distribution of NPV for Path H

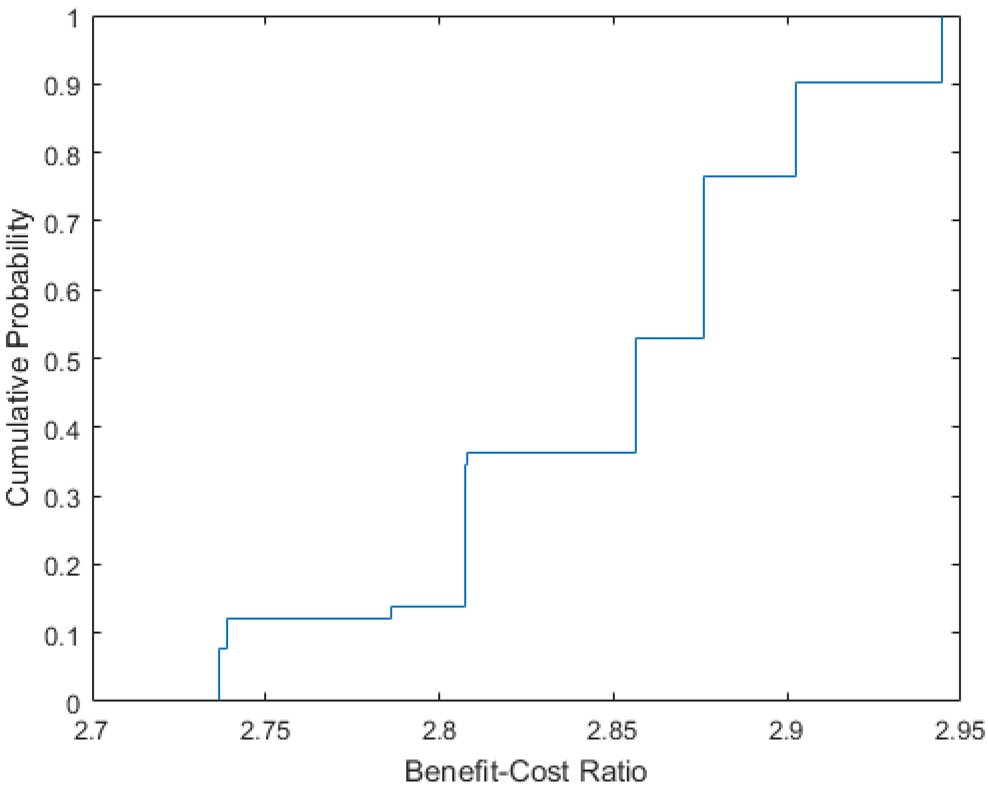


Figure B.27: Empirical Cumulative Distribution of BCR for Path I

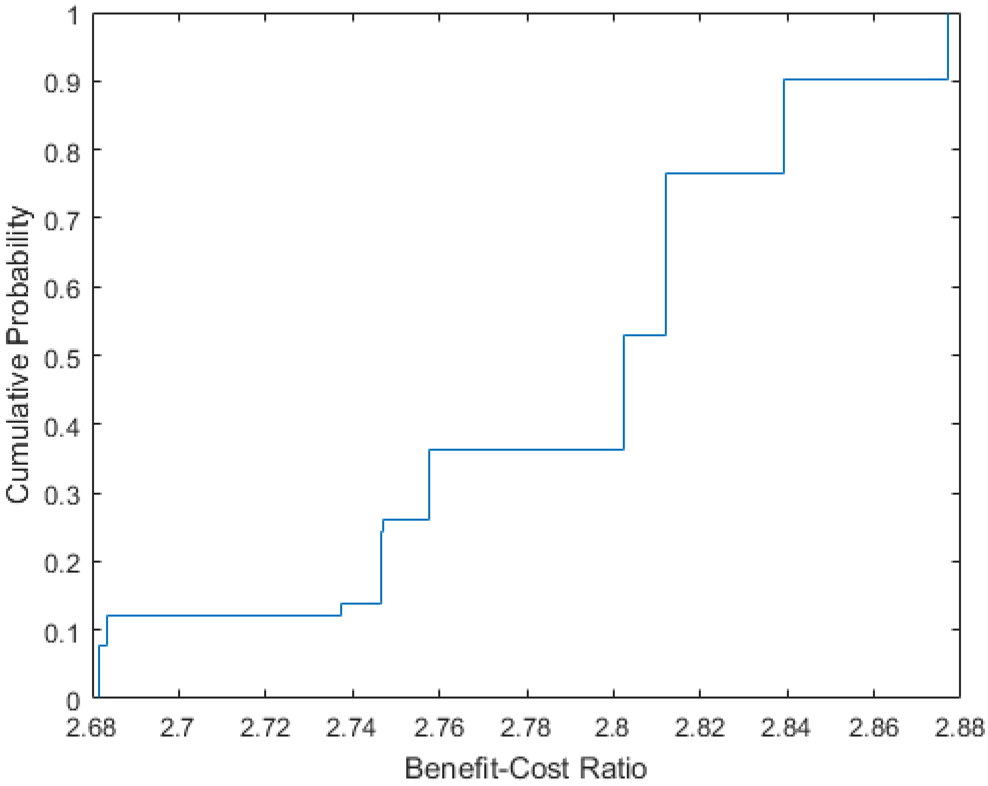


Figure B.28: Empirical Cumulative Distribution of BCR for Path J

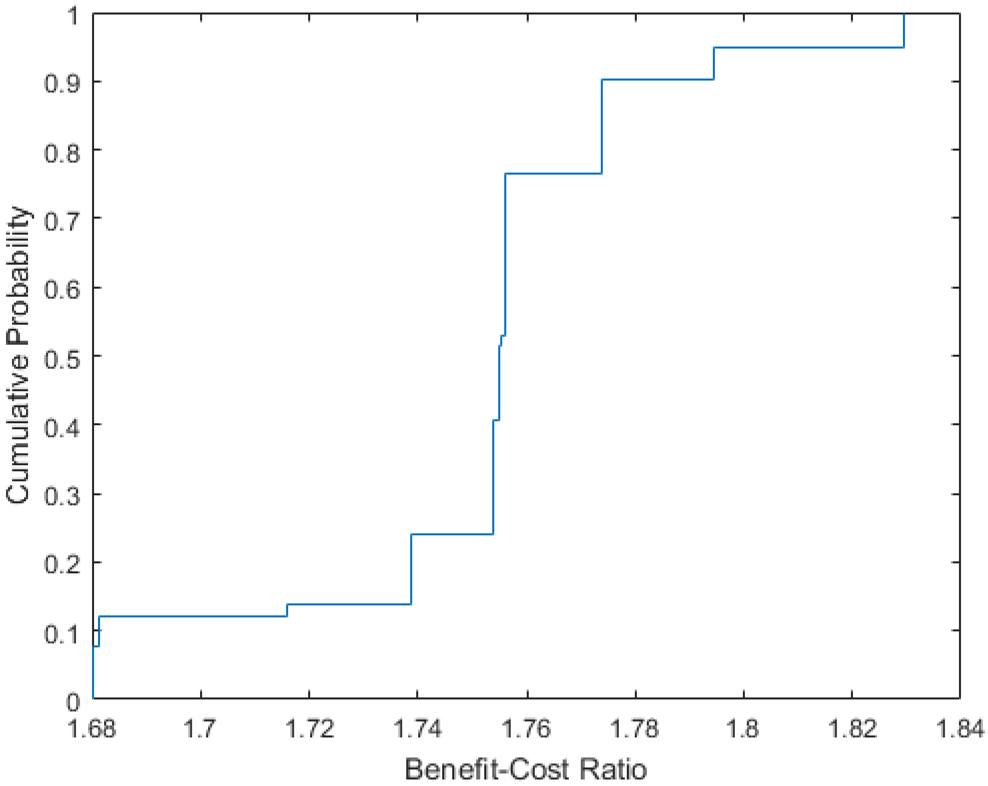


Figure B.29: Empirical Cumulative Distribution of BCR for Path K

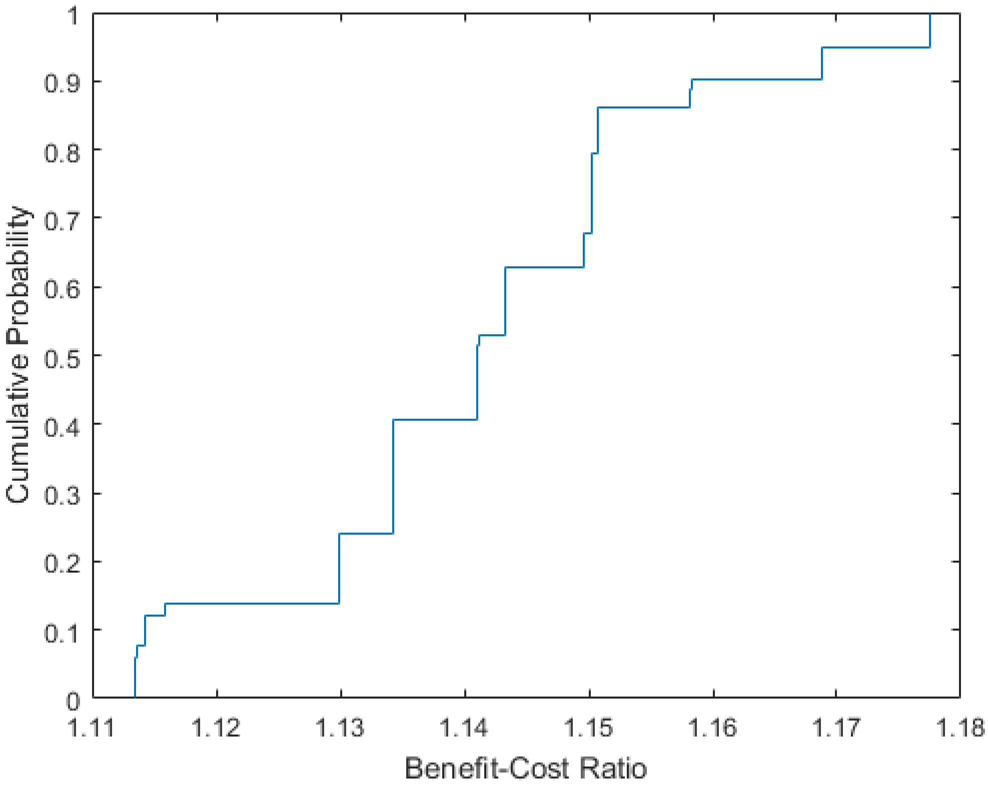


Figure B.30: Empirical Cumulative Distribution of BCR for Path L

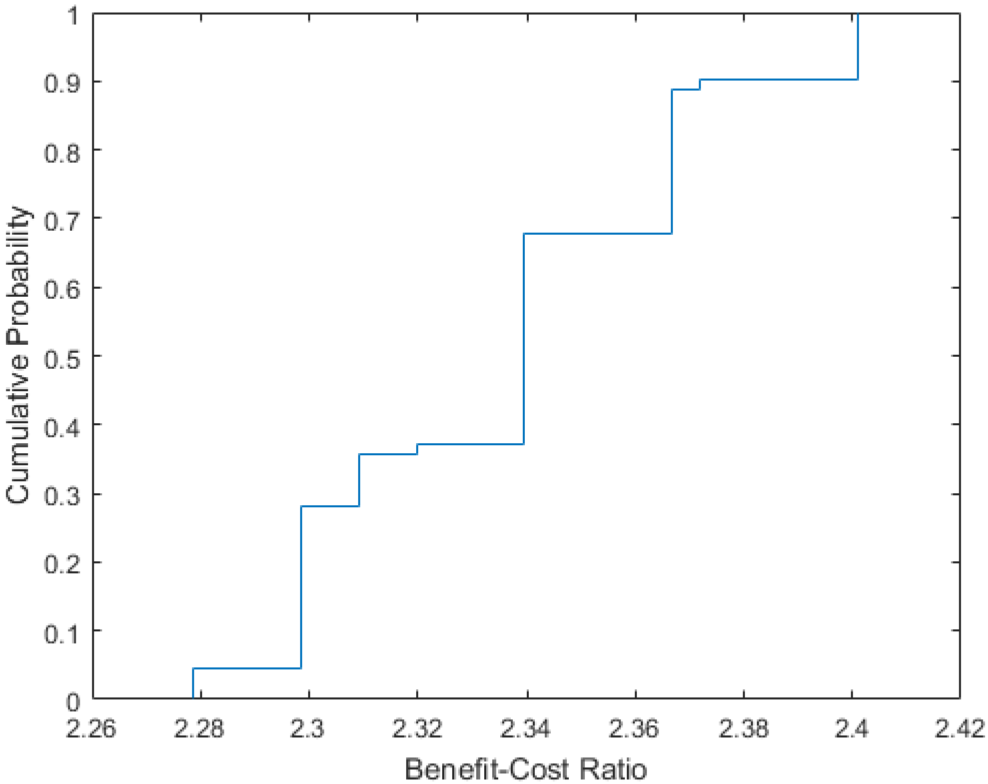


Figure B.31: Empirical Cumulative Distribution of BCR for Path M

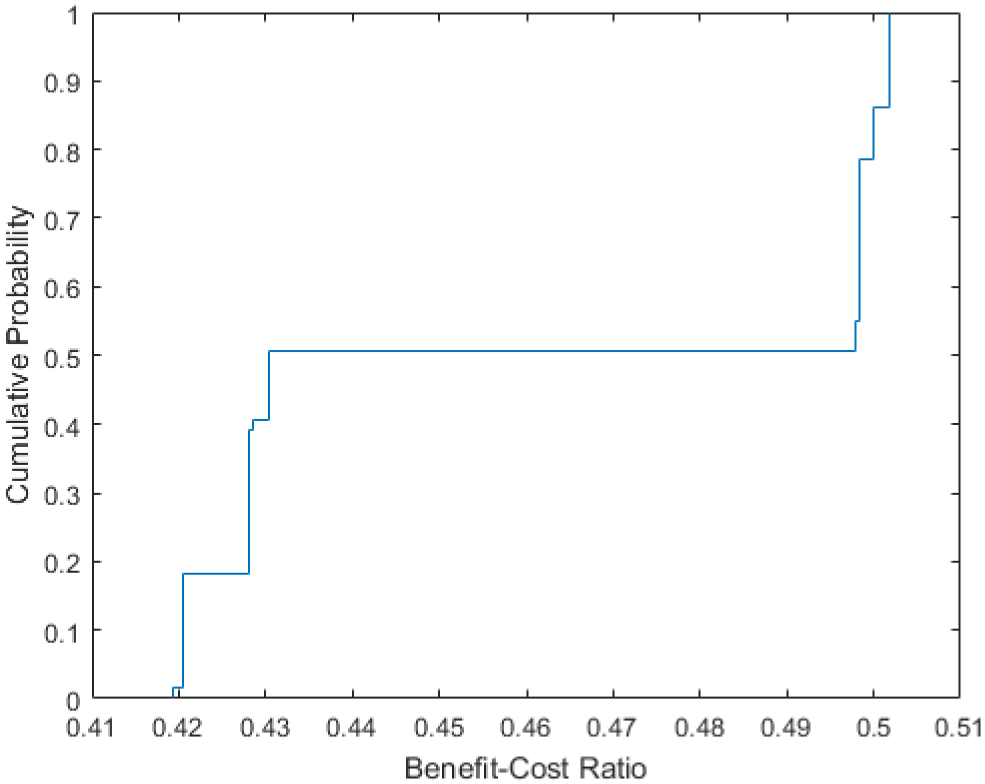


Figure B.32: Empirical Cumulative Distribution of BCR for Path N

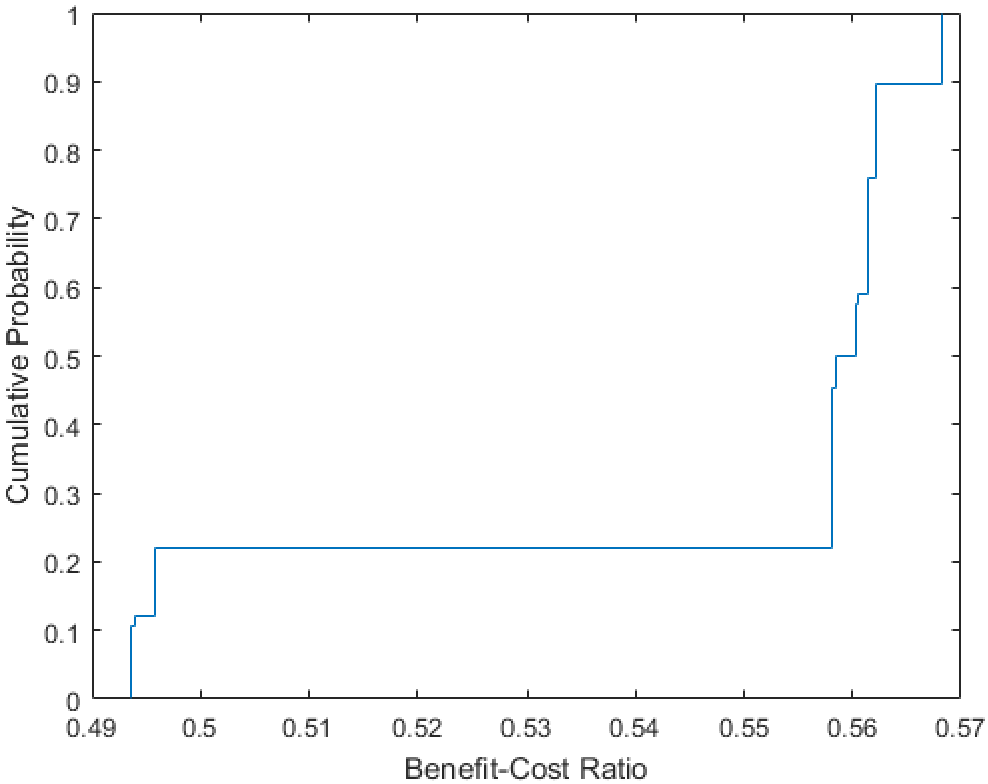


Figure B.33: Empirical Cumulative Distribution of BCR for Path O

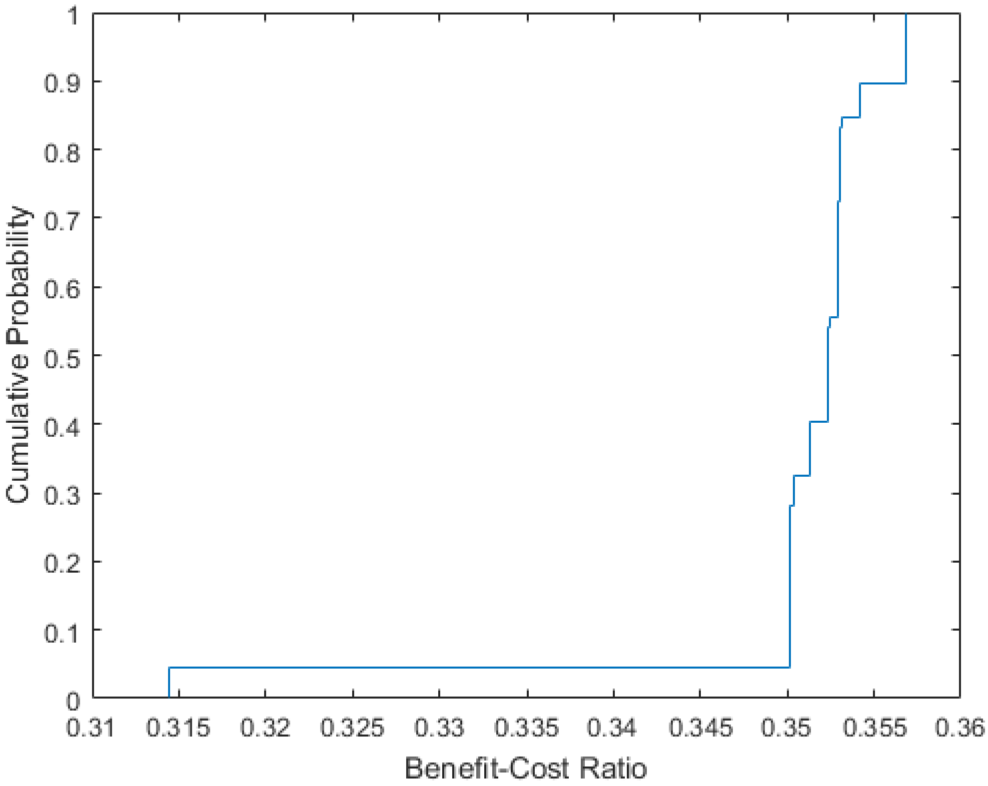


Figure B.34: Empirical Cumulative Distribution of BCR for Path P

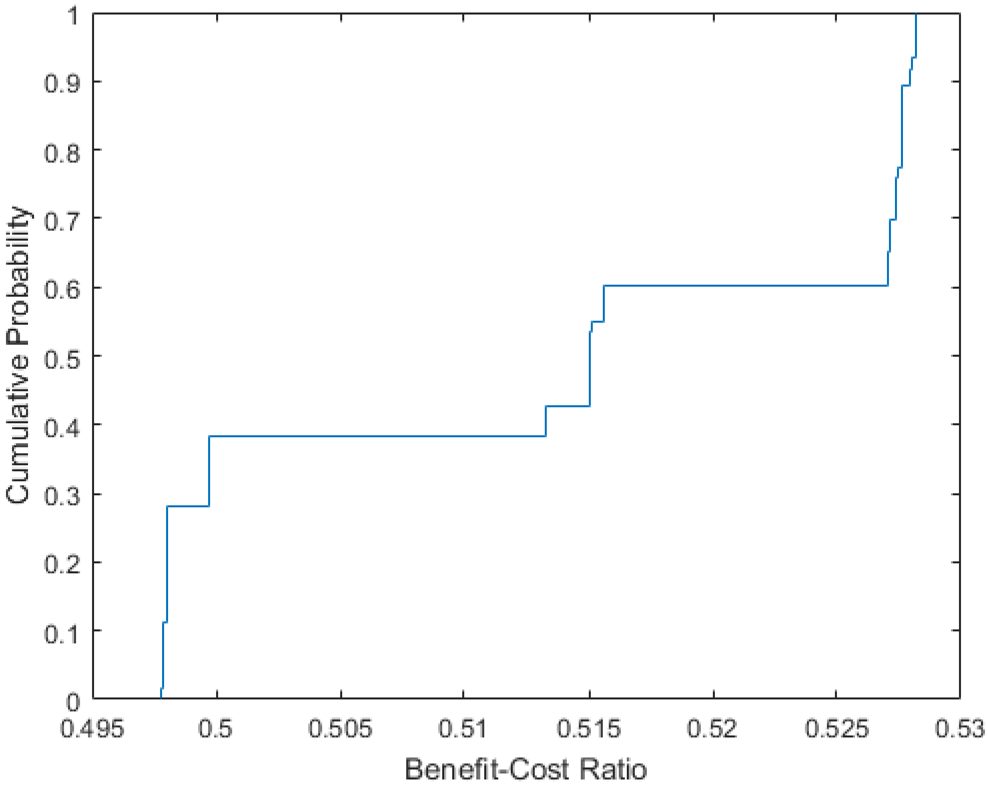


Figure B.35: Empirical Cumulative Distribution of BCR for Path Q

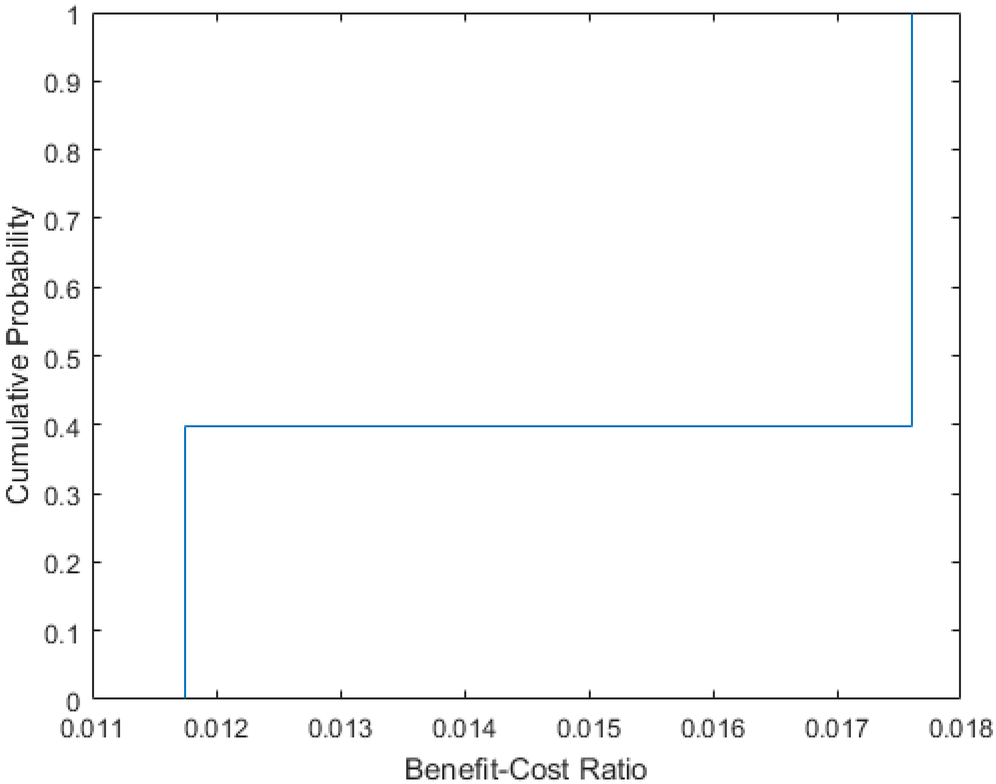


Figure B.36: Empirical Cumulative Distribution of BCR for Path R

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