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Assessing Urban Policy Adaptations to Pluvial Flooding and Stormwater Management under Climate Change

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Abstract

Increasing frequencies of heavy rainfall events in urban areas threaten to disrupt urban systems causing political, economic, social and environmental loses and damages. While cities make stormwater adaptation decisions, little is known if these decisions follow a similar pattern so that an adaptation framework can be developed to help cities facing similar stormwater adaptations in the future. The thesis is structed in three chapters based on three published articles. The first chapter explores the existing state of stormwater adaptations and the existing policy frameworks to make these decisions in six global and developed cities. The second chapter develops a combined Multi-Criteria Decision Analysis of the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to analyze the opinions towards stormwater management from select stakeholders with interest in the decision-making process. The third and final chapter uses the AHP-TOPSIS methodology to evaluate the opinions around stormwater management amongst the stakeholders in the six cities to identify if a decision hierarchy exists.

Executive Summary

Climate change is forcing cities to embrace new adaptations to increasingly dangerous extreme weather events. In particular, heavy rainfall events, or cloudbursts, are becoming more frequent in urban areas. By threatening to overwhelm existing urban stormwater infrastructure, these rainfall events can cause localized flooding damaging the economy, environment and social fabric of the city as well as damaging trust in the political systems of governance. As the world becomes increasingly urbanized, urban adaptations to stormwater will become more important in people's daily lives.

Urban climate adaptations are gathering in importance but still lag the more developed networks for climate change mitigation. Adaptation projects are often taken at a local level compared and as such there is no framework for adaptation for a global community to follow when compared to the overarching, national frameworks of carbon emission controls. Despite the local nature of adaptation, some cities share their knowledge and experiences with each other by joining international networks to foster an urban climate decision making community. These networks are effective incubators of policy, but their reach and scope remain limited. While incorporating local knowledge within an urban adaptation decision is important, the lack of an agreed upon framework or standards for adaptation leaves cities to create policy through trial and error independently. This is difficult for cities with fewer financial or technical skill resources who must make these adaptations in increasingly shorter time periods.

When making adaptation decisions cities must draw from the existing policy decision making tools at their disposal. However, these tools are often very technical excluding non-experts from understanding and embracing their internal mechanics. Within climate change discourses, cities are increasingly recognizing the importance of multiple stakeholders within the decision-making process, including those who have previously been excluded or center around grassroots movements. Cities must effectively join these various opinions and skill levels in order to effectively evaluate a policy decision.

Climate change adaptations rely on both climate science, in particular the hard sciences, technological advances and modelling, but also the social sciences, from economics to geography, political science and management. At the intersection of these

sciences lies the critical component of science communication. The science and management of climate change is an interdisciplinary field that draws on the experience from all these fields. This thesis, with a focus on social science, explores how cities are making urban stormwater adaptation decisions considering the increasing heavy rainfall events under climate change. By focusing on developed cities, I explore in this thesis how established, democratic cities must retrofit existing systems and explore new infrastructure and policy management techniques while incorporating multiple stakeholder involvement in the decision making process. In doing so the thesis answers three main aims:

1. To explore what are the existing adaptations cities utilize for stormwater management.
2. To construct a theoretically defensible Multi-Criteria Decision Analysis (MCDA) that is approachable for non-experts to increase transparency in the decision-making process.
3. To establish if an international framework for urban stormwater adaptations can be constructed.

The thesis is structured in three chapters, with each chapter principally dedicated to a corresponding aim. Additionally, each chapter has been published in international peer-reviewed journals.

Chapter 1, published in *Journal of Environmental Planning and Management* explores the existing adaptation strategies to urban stormwater management. The chapter demonstrates that while six developed cities; New York City (NYC), Vancouver, Sydney, Auckland, Copenhagen and Amsterdam, each present a different management approach towards cloudburst events, these six cities also use a mixture of five common policy alternatives to manage stormwater runoff. The scope of this work has previously been unexplored. Of these five alternatives: public green infrastructure, private green infrastructure, grey infrastructure overhauls, government streamlining and maintaining urban environments, public green infrastructure emerges as the future of best management practice for stormwater management. Thus, while individual cities might pursue different management approaches towards pluvial flooding, the repetition of the policy alternatives across these six cities as well as a shared focus on green solutions indicates the foundation of a global consensus towards the policy adaptation techniques available. As climate change continues to impact the urban environment, it is important to identify and understand policy tools for effective adaptation, ensuring knowledge can be transferred across all cities facing an unpredictable future.

Chapter 2, published in *Water*, is dedicated to establishing an accessible, yet theoretically defensible MCDA for urban stormwater adaptations. While green infrastructure has emerged as a focal adaptation technique for stormwater management, in order to craft adaptation policies cities must consider a multitude of emerging, complex and competing stakeholder interests around multiple adaptation alternatives. However, accounting for these different interests, analyzing their diverse priorities and maintaining a transparent decision-making process is not easily achieved within existing policy frameworks. This chapter defines and presents a combined Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) MCDA method that easily integrates and quantifies stakeholder priorities while remaining accessible for non-experts engaged in the policy making process. Demonstrating the method's effectiveness, the chapter analyzes opinions about stormwater adaptation in NYC across several stake-holder groups, easily identifying the differences and similarities in the opinions towards adaptation across the groups. The method succeeds in integrating quantitative and qualitative judgements, an important consideration for often uncertain decisions regarding climate change and the environment, indicating stakeholder preferential differences and allowing for more inclusive policy to be crafted. It can be extended beyond stormwater to many urban climate adaptation decisions facing multi-criteria considerations.

Chapter 3, also published at *Water*, establishes the extent a global framework for urban stormwater adaptation can be established. Currently, there are no global standards or frameworks for approaching urban rainfall adaptation policy and such standards or frameworks would allow cities that have limited time, finances or research capacities to make more confident adaptation policy decisions based on a globally agreed theoretical basis. Additionally, while adaptation via green infrastructure is often weighed against traditional grey infrastructure approaches, its choice must be considered within the context of the additional policy alternatives involved in stormwater management. The chapter engages with stakeholders located in the six cities across three key groups: those involved in governance, those involved in research and those involved in advocacy. Using the AHP-TOPSIS method defined in chapter 2, the chapter establishes trends in the opinions around stormwater decision making. The chapter demonstrates that green infrastructure undertaken by public bodies are the top policy alternative across the cities and stakeholder groups, and that there exists some consensus on best management practice techniques for urban stormwater adaptation. However, local and regional characteristics prevent a full adaptation framework from being established.

By successfully achieving the three aims, the thesis puts forward four overarching conclusions on the state of urban stormwater adaptations to climate change. First, the discourses around urban adaptation are focused on new green solutions alongside traditional grey infrastructure and that cities should increasingly consider environmental and social criteria in making these decisions on top of the traditional political and economic considerations. Second, the observed opinions of these discourses are often contradicted, with the stakeholders near uniform in their preferences for green infrastructure and distaste for grey infrastructure, despite its continued necessity. Additionally, the environmental and social criteria are still underweighted compared to the traditional economic and political considerations. The differences between the discussed discourses and observed opinions risks alienating stakeholders from the decision-making process and instills can distrust in urban governance and its capabilities to manage adaptation decisions. It is for this reason that third, only a loose framework for adaptation can be put forward considering green infrastructure as a top priority but cities will continue to need to consider their local situations for a full adaptation strategy. Finally, the AHP-TOPSIS methodology is demonstratively useful in complex climate change adaptation decision making and as such can be extended to additional adaptation issues to help increasing the transparency and accessibility of decision making.

There are several opportunities to extend the thesis into future work. This includes exploring the state of urban stormwater adaptation in non-westernized as well as developing cities to see if the conclusions from these wealthy, industrial, highly educated and developed cities can extend to other urban contexts. The policy alternatives should also be explored considering the multi-faceted nature of adaptations consolidating multiple urban problems into one adaptation decision. Additional MCDAs should be explored in an accessible manner to increase the amount of tools decision makers have to make policy decisions and increase science communication.

The differences between the theoretical decision and the observed preferences should be explored further with attempts to model these inconsistencies. Finally, the conditions that would trigger the preference for one alternative over another should be explored and modelled to observe the adaptation requirements over the variability of climate change and urban development projections.

Chapter 1: Existing Urban Policy Adaptation towards managing increasing Pluvial Flooding Events under Climate Change*

*Adapted from Axelsson, C., Soriani, S., Culligan, P. and Marcotullio, P. (2021) *Urban policy adaptation towards managing increasing pluvial flooding events under climate change*, Journal of Environmental Planning and Management, 64, 8, 1408-27.

1.1 Introduction

Cloudburst and rainstorm events cause flooding in urban areas. High volumes of rainfall paired with large areas of impervious surfaces can lead to widespread financial and social losses in cities during pluvial flooding. Climate change will exacerbate these problems. Regardless of changing rainfall totals in a region, most regions of the world are projected to see higher rainfall intensities (Donat *et al.* 2016). Alongside increasing urbanization, at times unmanaged, many cities will experience more cloudbursts and subsequent flooding events (Jiang *et al.* 2018). While confidence in climate projections cannot always be presented as high (Kundzewicz *et al.* 2014) and seasonal regional weather patterns can influence changes in precipitation (Tabari and Willems 2018), cities will have to prepare for an environment where disruptive flooding is more probable.

Cities are planning for a more intense rainfall future. Beyond local governance, some national entities are now providing guidelines for increased stormwater management (US EPA 2020a; 2020b). However, there are no universal guidelines for cities to adopt. In each locality, the regional geography will always influence the local rainfall patterns (Gonzalez *et al.* 2019) and the nonseasonal, localized nature of pluvial flooding makes it difficult to predict (NYC DEM 2019). Paired with local governance structures and local history, city strategies need to be unique to each location. Finally, despite preparation, there is always a chance that rainfall could overwhelm the stormwater system leading to localized flooding with climate change uncertainty further complicating the planning process (The City of Copenhagen 2012). As Waters *et al*. (2003) state, cities will have to expand the extent and capacity of stormwater infrastructure to handle the increases in stormwater.

While there is no guide for how to manage pluvial flooding, green infrastructure is an example of stormwater management best practice with considerable momentum.

Green spaces, including urban green spaces are effective at absorbing water and delaying stormwater runoff (Alexander *et al.* 2019; Moore *et al.* 2016). Absorbing stormwater emerges as a priority for cities facing increases in rainfall intensity. Green infrastructure supports traditional stormwater systems and helps fill gaps in coverage in dense urban areas (Ellis 2013). It is favourable due to its low cost compared to traditional stormwater systems (Moore *et al.* 2016) and fits within the policy narrative of many sustainable city goals. Green infrastructure is also capable of being scaled from individual projects to landscape initiatives giving it great flexibility in the policy framework (Carter *et al.* 2018). However, green infrastructure is most effective when it is supported by robust planning with clear strategies and management oversight (Jiang *et al.* 2018). Nonetheless, green infrastructure is integrated with other urban stormwater management policies but the extent it is utilized is at the discretion of the individual locality.

Even with climate change mitigation, urban adaptation remains crucial to combat the effects of un-avoidable climate change (Zhou *et al.* 2018). As with most forms of urban policy, there exists a disconnect between turning best practice policy into best practice management (Henstra *et al.* 2019). Discrepancies in jurisdiction, agencies and interests can prevent policy becoming reality. This is further hindered by the confusion of the role of public stakeholders in stormwater management projects (Uittenbroek *et al.* 2019). Thus, cities will need to adopt clear and robust policy alternatives to prevent against increased pluvial flooding.

Global urbanization increases the need for climate change adaptation strategies to manage pluvial flooding. By 2050, 68% of the world is predicted to be urban, with the developed regions North America, Western Europe and Australasia seeing these rates and higher already by 2018 (UN DESA 2019). As global urbanization increases, adaptation to urban climate issues becomes more important to nation states. This is increasingly important as some cities emerge as economic representations of nation states on the global stage (Crouch and Le Gales 2012). Individual cities are not alone in identifying climate change adaptations. Specifically, cities begin sharing resources, knowledge and skills, by engaging in and creating a city-based network of support and information (Goh 2019). Therefore, urban policy flows between regions without nation state involvement emphasizing the importance of urban centres in policy development. Furthermore, the future climate of certain cities may resemble the current climate of other cities today (Bastin *et al.* 2019). The sharing of solutions will help foster better urban adaptation from all cities.

Environmental damages threaten city systems. Economic losses, urban disruptions and the risk to human health and wellbeing disrupt city function. Repeated flooding events and damages may reduce the attractiveness and competitive edge of the city in the future. Developed cities, through their histories of growth, have complex and ageing infrastructure systems that require retrofitting to meet adaptation requirements (Kessler 2011). As developed cities have low rates of informal settlements, urban adaptation is almost exclusively performed through formal governance and guidance emphasizing the importance of good policy. To maintain global status, developed cities need robust adaptation methods.

Adaptation to flooding events presents cities with new opportunities. New governmental organizations can develop alongside new entrepreneurial and economic capacities. Cities can also engage in larger global discussions and connect their adaptation to the Sustainable Development Goals, particularly goal 11, Sustainable Cities and Communities (United Nations 2020). Cities risk losses from flooding events but are also provided the opportunity for adaptive growth.

This chapter presents the state of urban adaptation to climate change induced pluvial flooding through cloudburst and rainfall events in six developed cities in North America, Europe and Australasia. Section 1.2 outlines the methodology while section 1.3 establish discusses the management narrative of each case-study city in combating flooding events within the context of climate adaptation using their guiding policy documents. Following in Section 1.4 is a discussion and comparison of the five policy alternatives that these cities utilize in this adaptation. Finally, Section 1.5 concludes with recommendations and connections for other cities.

1.2 Methodology

This chapter examines the directions in urban policy towards cloudburst events and pluvial flooding through publicly available policy documents. A four-step process is applied to reveal the directions of urban stormwater management policy. The first step identifies the case cities (figure 1.1). We consider thirty-one coastal cities from three developed regions; North America, Western Europe and Australasia due to the collection of urban data, transparency of city governments, direct connections to aquatic

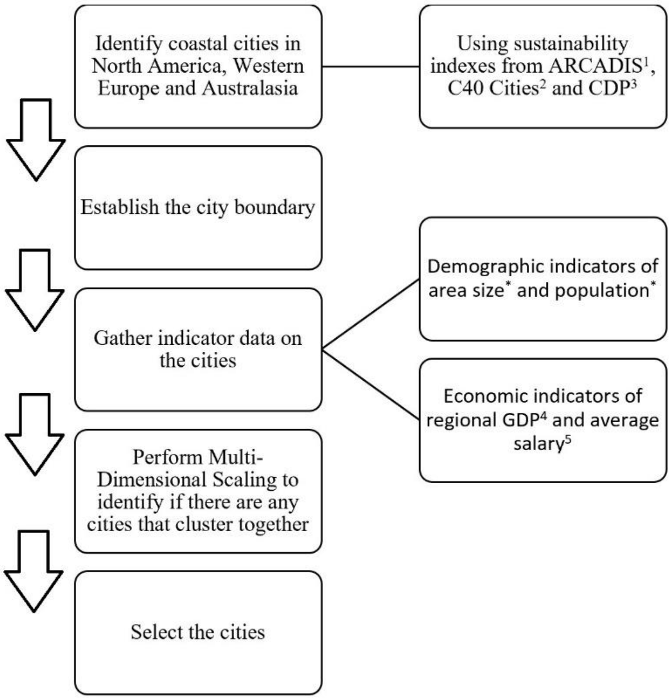

*Figure 1.1: Process for city selection; 1. ARCADIS 2018, 2. C40 2019, 3. CDP 2019, 4. Berube et al. 2015, 5. Payscale 2019, *Acquired from respective city governments*

and marine environments and high prevalence of English. After defining the cities, the research considers multi-dimensional scaling (MDS) using indicators to capture city size and urban wealth to enact policies. Additional multi-dimensional scaling was performed using similar demographic indicators alongside the environmental indicators average annual rainfall (extracted from the respective city governments) and the national Environmental Performance Index (EPI) (Yale Center for Environmental Law and Policy 2021). The resulting plots produced no clustering of cities and thus six cities, two from each region, were selected that capture the geographic spread of the regions as well as embody national and international importance in urban governance; New York City (NYC) and Vancouver (North America), the City of Sydney and Auckland (Australasia), and Amsterdam and Copenhagen (Europe) (figure 1.2). Please refer to Appendix 1.1 for the full MDS results. Considering the Australasian cities, the City of Sydney refers to the area governed by the City of Sydney Council, not the entirety of the urban region and Auckland refers to the jurisdiction of the Auckland Council. All six cities have readily available documents in English and capture varying sizes in geographies, population and economies.

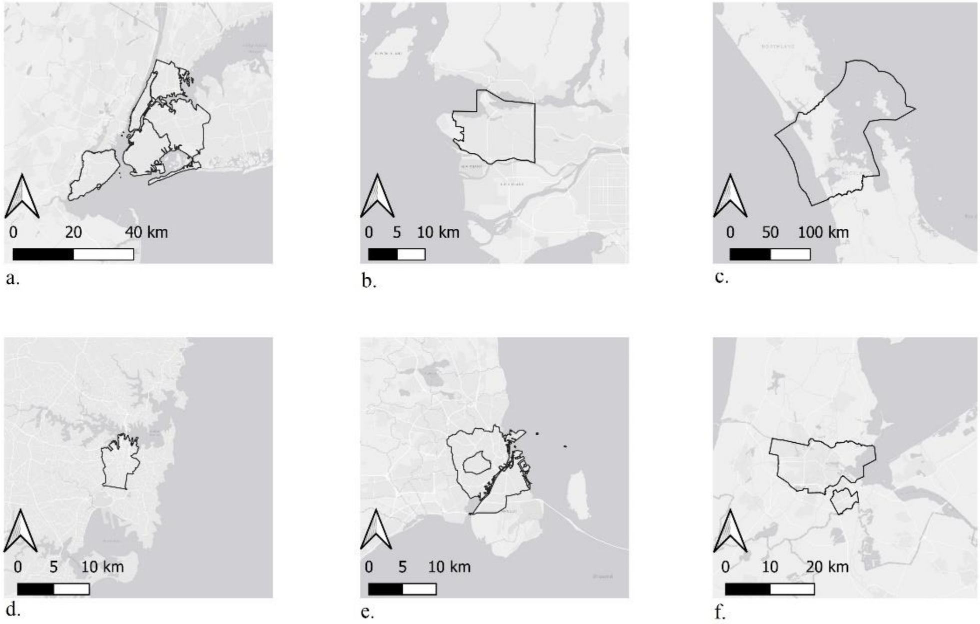

Figure 1.2: Boundaries of the six cities; a. New York City by borough, b. Vancouver, c. Auckland including maritime jurisdiction, d. City of Sydney, e. Copenhagen, f. Amsterdam

The second stage identifies the guiding policy documents and discusses the management style for heavy rainfall events in each city. We focus on those documents which set out a policy agenda and represent a framework for policy rather than legislation and ordinances. The documents are freely available on government or agency websites, published in English and regard water, stormwater, sustainability, urban or infrastructure management and development. The first documents were taken from each city's environmental, water and sustainability agencies' resources. Further documents were found through the self-referencing and discussion of the city policies. Within the documents, attention was payed to keywords of "rainfall", "stormwater" and "flooding". City jurisdiction differs between the three regions and the documents examined were produced for the municipal level and not the state/province or national level. A total of fifty-eight documents are included and the number of documents analysed for each city is dependent on the availability of the documents and where appropriate the most updated version of the document is used. Here we do not consider the development of specific policy documents over time but rather the publishing of guiding policy temporally. We acknowledge that the lower number of documents for

Copenhagen and Amsterdam may be attributed to linguistic barriers. The documents are displayed in Table 1.1.

The third stage identifies five policy alternatives the cities utilize to combat cloudburst events. The policy alternatives include infrastructure, economic, political, social and environmental management styles. Five alternatives are identified as unique from one another minimizing conceptual overlaps. In practice, policy is rarely considered independent as the political, economic and social considerations often link policy decisions. For example, investments in one technology may reduce the refurbishment cost of an infrastructure system while eliminating the requirement to build a second system and introducing the need for a tax to pay for the project. Here we do not consider the linkages between the alternatives but represent them as independent while acknowledging in policy they are often not standalone. Based on these alternatives, a discussion rate represented as a percentage is determined for each alternative in each city by taking the number of documents that mention an alternative divided by the total number of documents in the city. We acknowledge that not all documents are equally important in the management of stormwater, however, the translation to percentages allows for a discussion of direct comparison.

In the fourth stage, an additional six cities were selected from the study area: San Francisco and Boston (North America), Wellington and Brisbane (Australasia), and Dublin and Oslo (Europe). Similar policy documents within these six cities are analysed and the discussion rate of the five alternatives presented in order to observe how the alternatives perform in these additional cities and to confirm if they are more universally discussed within the three regions. The additional documents can be found in Table 1.2.

Table 1.1: Urban policy documents regarding pluvial flood management in the six case cities. Please refer to Appendix 1.2 for a list of references.

City	Policy	Re/ Publication Date
a. New York City	i. Solid Waste Management Plan	2006
	ii. NYC Wastewater Resiliency Plan: Climate Risk Assessment and Adaptation	2013
	iii. PlaNYC	2013
	iv. One New York City: One Water Sustainable Water Management for New York City's People and Environment	2015
	v. Cloudburst Resiliency Planning Study Executive Summary	2017
	vi. NYC Green Infrastructure 2018 Annual Report	2018
	vii. Climate Resiliency Design Guidelines	2019
	viii. Green Infrastructure (NYC DEP website)	2019
	ix. GreeNYC (website)	2019
	x. New York City Panel on Climate Change 2019 Report	2019
	xi. NYC Stormwater Management Program	2019
	xii. NYC's Risk Landscape: A Guide to Hazard Mitigation	2019
	xiii. OneNYC 2050	2019
	xiv. Stormwater (NYC DEP website)	2019
b. Vancouver	i. Integrated Liquid Waste and Resource Management (ILWRM) (Greater Vancouver)	2010
	ii. Greenest City 2020 Action Plan	2011
	iii. Climate Change Adaptation Strategy	2012
	iv. Greenest City 2020 Action Plan: Pat Two 2015-2020	2015
	v. Administrative Report to City Council on the Integrated Rainwater Management Plan	2016
	vi. Citywide Integrated rainwater Management Plan Volume I	2016
	vii. Citywide Integrated Rainwater Management Plan Volume II	2016
	viii. Region-wide Baseline for On-site Stormwater Management	2017
	ix. Policy Report to City Council on the Climate Change Adaptation Strategy	2018
	x. Study of the impacts of Climate Change on Precipitation and Stormwater Management	2018
	xi. Biennale Report Volume I (ILWRM)	2019
	xii. Biennale Report Volume II (ILWRM)	2019
	xiii. Resilient Vancouver	2019
c. Sydney	i. City of Sydney Recycled Water Plan	2012
	ii. Decentralised Water Master Plan 2012-2030	2012
	iii. Decentralised Water Master Plan WSUD and Stormwater Infrastructure Report	2012
	iv. 2017 Metropolitan Water Plan	2017
	v. Adapting for Climate Change: A long term Strategy of the City of Sydney	2017
	vi. Environmental Action 2016-2021 Strategy and Action Plan	2017
	vii. Stormwater Drainage Manual	2017
	viii. Sustainable Sydney 2030 Community Strategic Plan 2017-2021	2017
	ix. Resilient Sydney: A strategy for city resilience	2018
	x. Water Sensitive Sydney Summit Summary	2018
d. Auckland	i. Stormwater Asset Management Plan 2015-2045 Version I	2015
	ii. Stormwater Bylaw	2015
	iii. Auckland Growing Greener	2016
	iv. Auckland Unitary Plan	2016
	v. Resilient Auckland: Auckland civil defence and emergency management group plan 2016-2021	2016
	vi. Auckland Plan 2050	2018
	vii. Health Waters: Asset Management Plan Summary	2018

	viii. Stormwater Management Devices in the Auckland Region	2018
	ix. Our Water Future A Discussion Document Executive Summary	2019
	x. Stormwater forms and guides (website Auckland Council)	2019
	xi. Water Sensitive Design (website Auckland Council)	2019
e. Copenhagen	i. Copenhagen City of Architecture: The architecture policy of the city of Copenhagen	2010
	ii. Copenhagen Climate Adaptation Plan	2012
	iii. The City of Copenhagen Cloudburst Management Plan 2012	2012
	iv. Climate Change Adaptation and Investment Statement Part I	2015
	v. Climate Change Adaptation and Investment Statement Part II	2015
f. Amsterdam	i. Amsterdam Rainproof Brochure	2014
	ii. Amsterdam Rainproof Magazine	2014
	iii. Plan Amsterdam Building a Green City	2017
	iv. Plan Amsterdam A Global Review on Urban Strategies	2018
	v. Amsterdam Rainproof (website)	2019

1.2.1 Urban Stormwater Infrastructure

Stormwater infrastructure in cities is categorized by grey, green or blue/blue-green infrastructure. Here we consider green infrastructure to "[encompass] a variety of water management practices… that capture, filter, and reduce stormwater… It mimics natural hydrological processes and uses natural elements…" (Denchak 2019). Green infrastructure usually, but not necessarily, incorporates some form of visual greenery. Grey infrastructure in contrast is a mixture of hard traditional management techniques towards stormwater. While most green infrastructure projects are beneficial to water management, blue infrastructure, or green-blue infrastructure, can be viewed as a type of green infrastructure that focuses specifically on water systems. Some infrastructure projects can fall into multiple categories depending on the methods used. For example, subsurface detention systems can be grey, green or blue depending on if the purpose is to absorb stormwater into the ground, delay its release to the stormwater network or integrate it into the city water network (figure 1.3).

Table 1.2: Urban policy documents regarding pluvial flood management in the additional six cities. Please refer to Appendix 1.3 for a list of references.

City	Policy	Re/ Publication Date
a. Boston	i. Greenovate Boston 2014 Climate Action Plan Update	2014
	ii. Climate Ready Boston Executive Summary	2016
	iii. City of Boston Natural Hazard Mitigation Plan	2016
	iv. Climate Resilient Design Standards & Guidelines	2018
	v. City of Boston Climate Action Plan 2019 Update	2019
	vi. 2020 Stormwater Management Report	2021
b. San Francisco	i. San Francisco Urban Forest Plan	2014
	ii. 2015 Urban Water Management Plan	2016
	iii. Resilient San Francisco	2016
	iv. San Francisco Municipal Progress Report	2018
	v. Hazards and Climate Resilience Plan	2020
	vi. San Francisco Climate Action Plan Draft	2020
	vii. The City and County of San Francisco Capital Plan 2020-2029	2020
c. Wellington	i. Three Waters: Summary Asset Management Plan	2011
	ii. Stage 1 ICMP Development: Sumarry March 2014	2014
	iii. Wellington Urban Growth Plan 2014-2043	2015
	iv. Wellington Resilience Strategy	2017
	v. Wellington City Council's Long Term Plan 2018-2028	2018
	vi. Wellington Towards 2040: Smart Capital	2020
	vii. Water Sensitive Urban Design: A guide for WSUD stormwater management in Wellington	2021
d. Brisbane	i. Brisbane Long Term Infrastructure Plan 2012-2031	2012
	ii. Brisbane Vision 2031	2013
	iii. Brisbane's Total Water Cycle Management Plan	2013
	iv. Brisbane's FloodSmart Future Strategy 2012-2031	2013
	v. WaterSmart Strategy	2015
	vi. Brisbane Clean, Green, Sustainable 2017-2031	2017
	vii. Brisbane City Plan 2014	2021
e. Oslo	Urban Ecology Programme 2011-2026	2011
	Climate Change Adaptation Strategy for the City of Oslo 2014-2030	2014
	Action Plan for Stormwater Management in the City of Oslo: Executive Summary	2016
	European Green Capital: Oslo 2019 Application	2017
	The Urban Development of Oslo	2018
	Oslo European Green Capital 2019 Final Report	2019
	Green Oslo (website Oslo Kommune)	2021
f. Dublin	Dublin City Development Plan 2016-2022 Written Statement	2016
	Dublin City Council Climate Change Action Plan 2019-2024	2019
	Dublin City Parks Strategy 2019-2022	2019
	Dublin City Council Climate Change Action Plan 2019-2024 Annual Progress Report 2020	2020
	Water and Wastewater (website Dublin City Council)	2021
	Flood Projects and Water Framework Directive (website Dublin City Council)	2021

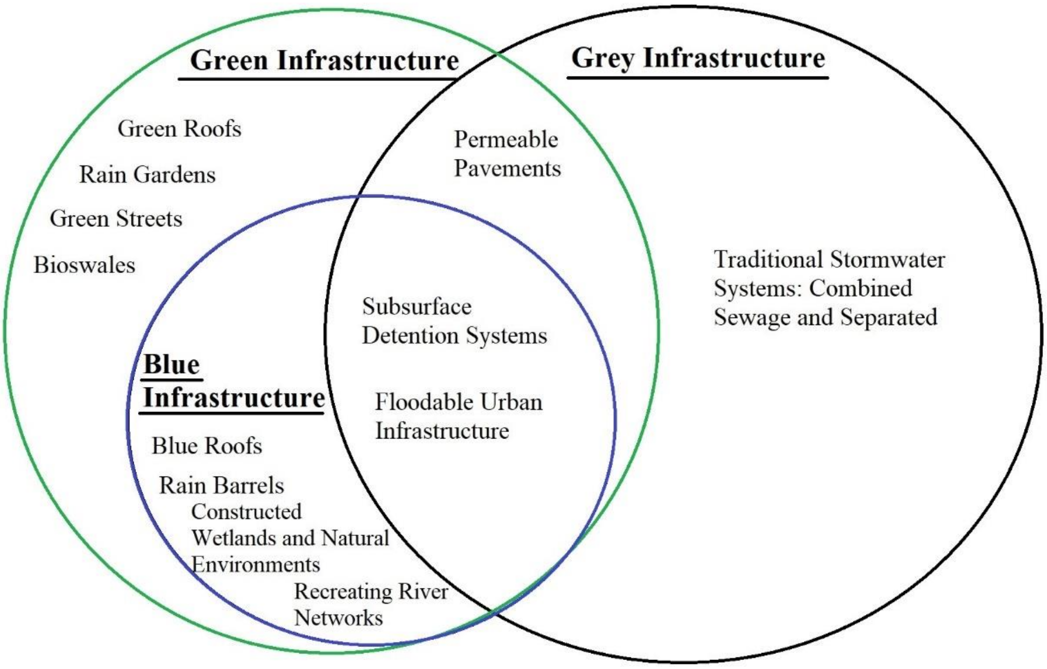

Figure 1.3: Examples and the overlapping relationships of green, blue (green-blue) and grey infrastructure. Source: US EPA 2020a, NYC DEP 2020

1.3 City Management Narratives

The following presents the six case cities and their policy management narratives towards pluvial flooding.

1.3.1 New York City

NYC is the most populated of the selected global coastal case cities at over 8 million people in roughly 784km2 (City of New York 2020). Due to the city's large size, cloudburst flooding is just one of the many urban issues requiring attention from policy makers (Table 1.1, a.xiii). Further complicating management, rainfall in NYC is neither predictable nor seasonal and difficult to account for (Table 1.1, a.xii). Additionally, low lying coastal areas, particularly prone to coastal and pluvial flooding, tend to be home to more vulnerable populations in the city (Faber 2015) (Table 1.1, a.x (ch1)). Finally, pluvial flooding is not the only type of flooding the city regularly experiences as tidal, coastal and fluvial flooding all contribute to the city's water management strategies (Table 1.1, a.xii). The city must attempt to balance these issues while trying to prevent the consequences of cloudbursts.

NYC's policy focus on sustainably managing pluvial flooding is relatively recent. While the PlaNYC document existed in stages since the mid-2000s, it was not until after Hurricane Sandy in 2012 that flooding within the city took focus (Table 1.1, a.iii). The storm surges of Sandy reinvigorated the discussion about the wastewater network and stormwater system, continuing through the late-2010s as OneNYC became the guiding document on NYC sustainability (Table 1.1, a.iv; a.xiii). In particular, eliminating combined sewage overflow (CSO) events became a wastewater priority as they represent a large threat to the NYC aquatic environment (Table 1.1, a.iv; a.vi; a.xi; a.xiii). Managing cloudburst flooding intuitively fits within these plans to reduce rainfall loads and separate stormwater systems. However, there is still room for improvement in NYC's response as recent events expose. In July 2019 as 24-hour rainfall totals reached upwards of 88mm, vehicles were submerged, and streets impassibly flooded (Cappucci 2019). Targeting existing stormwater infrastructure alone is not enough to mitigate these high intensity rainfall events and despite the inclusion of stormwater in sustainability documents, pluvial flooding continues to threaten NYC. Extra attention is needed for cloudbursts.

NYC is forming policy to directly manage rainfall flooding. The city acknowledges that rainfall poses a significant threat to the city while volumes are increasing (Table 1.1, a.x (ex ch2 ch7)). However, there is no city-wide cloudburst management strategy, only local initiatives (Table 1.1, a.v). Local action can open the door for citywide management but while waiting on the results of neighbourhood action, other areas in the city will continue to suffer the results of cloudburst flooding. Nonetheless, NYC is following trends in best practice management by embracing green infrastructure including blue infrastructure strategies (Table 1.1, a.iv; a.vii; a.viii; a.x (ch7); a.xi; a.xiv). The city is framing these alternatives as cheaper and easier than grey infrastructure despite the city's continued investment and policy focus in wastewater grey infrastructure overhauls. While the city lacks a unified rainfall management approach, it is beginning to directly use policy towards cloudbursts while tying it in with other management types.

1.3.2 Vancouver

Vancouver's commitment to managing pluvial flooding has been increasingly frequent over the past decade. At over 630,000 people in roughly 115km2, the city of Vancouver is the corner stone of the larger metropolitan area (City of Vancouver 2020).

Since the early 2010s, the Greenest City Action Plan (Table 1.1, bii; biv) provides the basis of sustainability giving Vancouver the opportunity to adapt and develop specific environmental and climate change plans beyond the general premise of “going green”. For rainfall, this manifests in the integrated rainwater management plans of 2016 (Table 1.1, b.v; b.vi; b.vii). As insurance claims from pluvial flooding, already a concern in the city (Table 1.1, b.iii; b.ix), will only increase with rainfall intensities, Vancouver is committed to providing reliable rainfall management. Events, such as a flash flooding event in December 2018 where upwards of 49mm of rain fell in 24 hours (Floodlist News 2018), demonstrate Vancouver’s need for stormwater management.

An underlying theme in Vancouver’s policy is a commitment to environmentalism. The city almost presents an apologetic tone in recognizing that grey infrastructure is critical to handle the city’s rainfall alongside green developments (Table 1.1, b.v). Nonetheless, even these infrastructure overhauls and developments are still mindful to the ecosystem as the protection of the marine environment through the removal of CSOs remains a priority (Table 1.1, b.i; b.iv; b.v; b.xi; b.xii; b.xiii). With a reputation emerging for being green, Vancouver is aware of the appeal that the natural environment has not just for residents but tourism. By investing in green solutions for rainfall management, the city can protect the environment, prevent flooding and further develop a reputation of being green. Similarly, the reestablishment and mimicry of natural environments not only provides solutions for stormwater runoff but also increases the total natural environment (Table 1.1, b.vi; b.vii). This narrative of environmentalism allows Vancouver to tackle many problems at once. By providing green investments in stormwater management, the city can link these solutions back to other targets and goals in their central Greenest City Action Plan such as carbon consumption, clean air, agriculture and the green economy (Table 1.1, b.ii).

Vancouver is not solely committed to infrastructure projects to manage the increasing volumes of rainfall. Softer management approaches are directly integrated into their policy frameworks. Waste management, educational programs, public outreach and construction/zoning codes all contribute to the city’s ability to effectively manage stormwater (Table 1.1, b.vi; b.vii). Even with progress made in infrastructural development, without the public’s commitment to environmentalism the governmental policy cannot maximize full efficiency. Furthermore, these efforts do not just help with stormwater but can help the city begin to tackle other urban issues from climate change mitigation to employment to reducing confusion between governmental agencies. Vancouver has committed to better stormwater management and their policies reflect their commitment to environmentalism and integrated urban management.

1.3.3 Sydney

Sydney needs to manage rainfall not just to prevent flooding but to use the water as a resource. The smallest of the case cities at over 200,000 people in roughly 25km2, the City of Sydney represents the core central business district and urban centre of the Sydney Metropolitan Region, the largest in Australia (City of Sydney 2020). This allows the small government a large voice in directing policy in the region. Despite engaging with stormwater policy in the past decade, Sydney's environmental focus has largely been on their arid environment centralizing on drought, water scarcity and heat (Table 1.1, c. iv, c.v). As such, water must fit into this narrative of protecting the water supply and reducing heat. The development of water management alongside other urban management culminates in the document of Sustainable Sydney (Table 1.1 c.viii). Green infrastructure provides a solution for both water and heat management as Sydney advocates the inclusion of green spaces to reduce heat stress (Table 1.1, c.ix) while green spaces themselves capture stormwater. These green spaces also contribute to healthy urban communities, a target of Sustainable Sydney. For Sydney, stormwater may not be the principle problem, but it is integrated well into other management ideals.

Stormwater is a prize that Sydney can fully utilize and help reduce water shortages. As Sydney's climate gets warmer, stormwater recycling provides needed relief for the city (Table 1.1, c.i). Beyond the implications for the drinking water supply, capturing stormwater in Sydney is itself a resource for providing further stormwater protections as stormwater can support the green spaces developed to protect the urban environment. More captured stormwater through aquifer recharge or direct distribution can support more green spaces which can capture more stormwater, and the cycle continues. Sydney's earlier focus on these water sensitive urban design (WSUD) projects highlights their commitment to utilizing stormwater as a resource (Table 1.1, c.ii). Stormwater management for Sydney provides water security, but also prevents flooding.

Beyond heat management, Sydney is committed to reducing stormwater flooding. With urban growth and changing rainfall patterns placing pressures on existing infrastructure, the city must adapt to avoid flash flooding, sewage overflows, property damages and critical infrastructure disruptions (Table 1.1, c.v; c.x). Recent events such as in February 2020 where nearly 400mm of rainfall fell over four days have highlighted Sydney's continued need for flood management (BBC News 2020). As such, Sydney presents an argument where not just the city needs to incorporate stormwater management, but residents need to as well (Table 1.1, c.iii). This format of public and private investment in stormwater management helps ensure that flooding is minimalized but can also further be tied into their commitment for water capture. Stormwater can create flooding hazards within Sydney, but the city's management has adapted to take this water and use it as a resource.

1.3.4 Auckland

Auckland is a growing city and it is determined to prioritize sustainable infrastructural growth. Auckland, through the jurisdiction of the city council, has the largest area of the case cities at over 4,800km2 and a population of over 1.6 million (Auckland Council 2020). Throughout the latter half of the 2010s Auckland took serious consideration of sustainable growth and environmentalism while the Auckland Plan and Unitary Plan emerged as central guiding documents (Table 1.1, d.iv; d.vi). The benefits of green solutions to citizens, tourism and the environment as well as protecting cultural and indigenous heritage is clear to the policy makers and guides the policy narrative (Table 1.1, d.iii; d.vi; d.viii; d.xi). Therefore, flooding must not harm citizens and stormwater must not pollute the local landscape either through CSO events or pollutant loading (Table 1.1, d.iv, d.vi). As such, infrastructure development plays a large role in reducing potential damages from stormwater. However, despite pursuing grey and green alternatives in infrastructure, there is no unifying goal in how to achieve these reductions.

Clearer is the city's policy perspective to ensure that the city grows while not impeding on stormwater system development and the natural ecosystem. By concentrating urban development and protecting rural areas (Table 1.1, d.vii), Auckland is sending a clear message highlighting the importance of the natural environment. Consequently, these rural areas help better manage rainfall and concentrate urban infrastructural issues to a much smaller area. Ultimately, this policy decreases the burden of the city to manage new stormwater systems across their vast area. The council admits that while rainfall patterns are changing, they are likely to change less rapidly compared to population changes (Table 1.1, d.i). Therefore, directing urban growth can relieve the pressure of building new infrastructure systems.

Infrastructure is only one method utilized for rainfall and stormwater management in Auckland. Beyond government investments, Auckland encourages personal responsibility for stormwater. WSUDs can be translated to individual properties in the city and is important in reducing flooding potential at the source (Table 1.1, d.v, d.vii; d.viii, d.xi). Changing individual properties and citizens' responses to rainfall can greatly reduce the flooding potential in the city. Yet all this requires governmental planning and policy, something Auckland has not fully achieved. Other methods for protecting against runoff pollution include removing litter from the street (Table 1.1, d.iii) but even these actions require government oversight and management. To achieve their vision of reduced stormwater flooding and loading, Auckland needs to organize their response. Creating an integrated water system with drinking water, wastewater and stormwater allows the city to better manage how cloudbursts move throughout the city (Table 1.1, d.vii) but for now the policies are still not fully integrated. Meanwhile rainfall events continue to effect Auckland such as an event in November 2018 where 24-hour rainfall totals reached 70mm (NZ Herald 2018). Auckland provides a basis for integrated management of rainfall but has not fully realized these plans.

1.3.5 Copenhagen

Copenhagen, home to just under 800,000 people in roughly 180km2, is a global pioneer in heavy rainfall and urban flood management (Kobenhavns Kommune 2020). After suffering a devastating pluvial flood in July 2011 where 150mm of rain flooded the city in two hours, the city published the Cloudburst Management Plan in 2012 (Table 1.1, e.iii). Copenhagen's policy developed in the early 2010s and remains fundamental in the city development. The city developed a narrative where a wetter city requires better designed urban space to move water, the results of which rely heavily on green and blue infrastructure (Table 1.1, e.iii; e.iv; e.v). While moving stormwater, the city does not have policy to capture and integrate the water into the municipal system as they have difficulties in capturing, treating and integrating stormwater rather than releasing it directly to sea (Table 1.1, e.iii; e.iv; e.v). Copenhagen's plans are ambitious, and this comes with a cost. The city argues that removing stormwater through green solutions is cheaper compared to the costs of inaction and the expense of rehauling the entire sewage network (Table 1.1, e.iv; e.v) thus motivating the approval of financial resources. Copenhagen recognizes the threat of heavy rainfall and applies action towards its policies.

Cloudburst management in Copenhagen is scalable and adaptable. By focusing on neighbourhood strategies within the unified city guidance (Table 1.1, e.iii), Copenhagen maximizes efficiency in implementing policy while being able to apply lessons learned to other projects around the city. Additionally, this policy heavy and scalable approach presents Copenhagen with a knowledgeable and skilled industry they can export to other cities (Table 1.1, e.iv; e.v) furthering their status as a pioneer in management. Copenhagen's policy is comprehensive yet adaptable cementing the city's ability to constantly innovate rainfall solutions.

Rainfall is a priority issue for the city but is not the only issue. Sea level rise, the urban heat island and groundwater security threaten the city and climate change will worsen the problems (Table 1.1, e.ii). Beneficially, the green and blue networks created for cloudburst management provide adaptive capacity for other environment issues facing the city (Table 1.1, e.ii). By focusing on the need for flood management today, Copenhagen is future proofing the city for other hazards as climate change progresses. Similarly, the co-benefits from rainfall management permeate beyond the immediate environmental sector into other concerns for citizens from insurance claims to mould reduction to access to green space. Nonetheless, whatever the approach for urban sustainability and climate change, rainfall remains a central component for Copenhagen.

1.3.6 Amsterdam

Amsterdam presents a clear vision for managing cloudburst flooding. A city filled with canals, Amsterdam has a population of roughly 870,000 in an area approximately 165km2 (City of Amsterdam 2020). After a flooding even in July 2014 where roughly 56mm of rain fell in the urban region (Davies 2014), Amsterdam's policy geared towards cloudburst management. Amsterdam Rainproof, set up by the water utility company for Amsterdam, is a separate organization tasked with understanding and managing rainfall and cloudbursts in the city (Table 1.1, f.v). What makes this unique is that it is a separate agency that relies on stakeholder involvement from all facets of city life; government, utilities, businesses, property owners, education, residents, insurance markets etc. (Table 1.1, f.ii). The inclusion of these stakeholders ensures that developed policy is useful for the whole city. Additionally, the policy can easily permeate through the city and reach everyone as some stakeholders can act as middlemen for distributing government guidance in daily life. The independence of this organization also ensures that cohesive policy is being crafted for the city. The policy that Amsterdam puts forward has a clear understanding for how to connect the city and target the specific issue of rainfall management.

Urban design has a large role in Amsterdam's strategy. Large-scale public works take a big role in the policy put forward to tackle rainfall, particularly green infrastructure (Table 1.1, f.v). Yet these governmental projects make efforts to engage the local community and demonstrate the benefits of the projects. Amsterdam is committed to an inclusive management technique. However, Amsterdam Waterproof is also reliant on property owners sharing responsibility for green infrastructure with small-scale projects (Table 1.1, f.i; f.ii; f.v). It is not just a campaign to rainproof the city but to also rainproof your home, reuse water and reduce the pressure on the environment and utility company, and engage in the circular economy. Amsterdam wants not only the city but also its citizens to be stewards and take pride in protecting against rainfall flooding.

Amsterdam explicitly wants rainfall management to become a cornerstone of policy and permeate into all facets of the city. The city's plan encourages stakeholders to network and think together creatively (Table 1.1, f.ii). This collaboration can create solutions for problems beyond rainfall. As the priorities of the stakeholders become better understood by each other and intertwined, it will become impossible to ignore each other's concerns when creating solutions. This culture of engagement is beneficial to the city for every urban project. Rainfall management also contributes to other sustainable city priorities such as the Plan Amsterdam project (Table 1.1, f.ii; f.iv). If the ideas of rainproofing extend beyond one-off projects, the city will be better prepared for cloudburst events as rainfall will have been integrated into city functioning. Amsterdam presents a narrative of close collaboration to manage rainfall while providing a comprehensive collaborative approach to management.

1.4 Policy Alternatives

There are five main policy alternatives that the cities, despite their varying narratives, utilize to manage current and future flooding from cloudbursts; grey infrastructure, public green infrastructure, private green infrastructure, government streamlining and maintaining urban environments. These alternatives are distinct from each other in theory yet in practice city management blends them and uses them to support each other. Nonetheless, each of these five alternatives have their own characteristics and mitigate urban pluvial flooding in their own way using a blend of stakeholder involvement, financing, engineering and legislation. These policy alternatives form the basis in the decision-making process for rainfall flood management. The discussion rate of each alternative in the city policies is presented in Table 1.3.

1.4.1 Grey Infrastructure Overhauls

The first policy alternative for managing pluvial flooding and future proofing against cloudburst events is to manage, update and adapt the existing grey infrastructure. All six of the case cities include grey infrastructure in the majority of their policy documents with an average rate of 84% (Table 1.3). Only NYC has the lowest rate, 71%, despite their policy narrative focusing on the sewer/stormwater system. The consensus among the cities is that grey infrastructure is still an important and much needed policy alternative despite not always forming the backbone of policy narratives. There is a continued need in developed cities to retrofit dated infrastructure and remove CSO stormwater/sewage systems. However, by framing pluvial flooding alongside CSO events cities can use existing environmental protection legislation as a basis for rainfall management. By utilizing grey infrastructure cities can operate with existing governmental oversight in a familiar public works process.

Grey infrastructure plays a continuous role in the movement of water into or away from the city. There is a perpetual level of uncertainty with respect to how climate change will affect rainfall volumes and there is always a risk of these volumes overwhelming capacity, including gaps in green technologies. Grey infrastructure provides the facilities to move high volumes of water to prevent localized flooding as either a priority or a safety measure. The proven effectiveness of grey infrastructure in urban history ensures its continued usage. While grey infrastructure is not idealized by

Table 1.3: Discussion rates of the five policy alternatives within the six case cities

	Grey Infrastructure Overhauls	Public Green Infrastructure	Private Green Infrastructure	Government Streamlining	Maintaining Urban Environments
New York City (*n=14*)	71%*	71%*	36%*	21%*	36%*
Vancouver (*n=13*)	100%	100%	38%*	46%*	46%*
Sydney (*n=10*)	80%	80%	30%	80%	40%
Auckland (*n=11*)	91%*	73%*	36%*	36%*	64%*
Copenhagen (*n=5*)	80%	100%	100%	60%	40%
Amsterdam (*n=5*)	80%	100%	80%	60%	40%

*Rounded value

the case cities, it is a policy alternative that is already a large part of the urban system and needs to be considered in future scenarios.

1.4.2 Public Green Infrastructure

As a policy alternative public green infrastructure can be defined as infrastructure projects that are undertaken on public property or essential public infrastructure that is largely funded by the government. These projects, which are both big and small, scale from neighbourhood overhauls to an individual project. Similarly to grey infrastructure, all six cities place a high importance on public green infrastructure, with Copenhagen, Amsterdam and Vancouver fully incorporating the alternative into the policy narrative (Table 2). The alternative also demonstrates the highest average rate of all the alternatives at 87%. Public green infrastructure is a largely popular policy alternative within the case cities and is predominantly the focus of future developments.

Green infrastructure is a best practice tool and cities envision this through public financing. By having direct control over the infrastructure, cities have discretion to test the effectiveness of their policies and demonstrate their commitment to sustainability. The often visual component of green infrastructure, in contrast to non-visual policy initiatives such as education or more subsurface and hidden grey infrastructure, allows city leaders and elected officials to provide direct evidence of their actions while citizens get to enjoy the co-benefits of urban green spaces. As the alternative becomes more popular the city is more likely to find support in financing the infrastructure. With more financing, the city can experiment with scaling these infrastructure projects. Due to the existing governance structure, public green infrastructure is easily integrated into policy management and thus highly discussed.

Cities can use public green infrastructure and flood management as a doorway to begin remodelling the city into a greener vision of the 21st Century. Neighbourhood redevelopments with new public squares and parks, better designed roads, and more attractive critical infrastructure can help cities redefine their urban core into a more sustainable centre. As water management effects everyone and is an integral part of city management, it provides cities the opportunities to examine whole neighbourhoods and make positive environmental changes for the future. There is a large amount of rhetoric around green infrastructure and how it connects into the future sustainable and green vision of an urban future.

1.4.3 Private Green Infrastructure

Private green infrastructure includes infrastructure projects undertaken on private property that are largely financed privately or with government incentives. The scale of projects can vary from large office buildings to individual homes but the methods of achieving the green investments occur similarly. All six cities incorporate private green infrastructure into their strategies, but Amsterdam and Copenhagen take this alternative much further with 80% and 100% discussion rates (Table 2). Compared with the North American and Australasian cities incorporating this alternative only in 30-40% of the documents the European cities emerge as more intensive in promoting green projects beyond formal governance.

Despite varying discussion rates, all six cities recognize that while this alternative may seem smaller in comparison to public works, it is essential in securing urban areas against cloudburst flooding as private land is a major first point of contact for rainwater. Reducing the water loading to the public infrastructure can help minimize localized flooding and ensure city services are not overwhelmed during a cloudburst event. Private green infrastructure also connects citizens with resource management and can help lower other expenses such as cooling, heating and water usage thus enticing its implementation.

There are two issues that come with this alternative; space and financing. Cities need to convince property owners to dedicate space for green technologies where other utilities could be placed as well as convince them to incur the costs. The European cities, through their specific management protocols and agencies for cloudburst events, have a better system of encouraging this alternative to the general public. This structuring also allows the importance of this issue to permeate through the city government onto citizens. The North American and Australasian cities do not ignore this alternative but rather their systematic discussion of it does not always present it as a viable alternative when compared to larger infrastructure projects. Private green infrastructure can manifest in various ways throughout the city, but despite its often smaller scale it is important to fill the gaps between public spaces.

1.4.4 Government Streamlining

Cities can enact this policy alternative of streamlining their government systems to better protect against cloudburst flooding. This alternative includes a mix of government reorganization, particularly the merging of water, stormwater and wastewater systems as well as civil servant education and producing a framework for management goals. Perhaps one of the most important alternatives as it lays the foundation for urban management, all six cities include this alternative in their management strategy as the guiding policy documents themselves are a form of this alternative (Table 2). However, the rates of explicit discussion of this method within the documents is varied. Sydney mentions this the most (80%), as a product of their need for water as a resource as well as the complex levels of jurisdiction between the city, region, state and water companies. The European cities and Vancouver take a more moderate approach to streamlining while Auckland and NYC have the lowest discussion rates. The variations in the discussion rates of government streamlining highlight that while all cities include guiding policy documents there is disagreement as to how far governmental management should and can change.

As a city grows, the more complex its government becomes making reorganization more difficult. The two largest cities, NYC and Auckland, embody this problem in their discussion rates. This alternative is crucial in effective urban rainfall management due to the sectorization of the issue. Green spaces, roads, parks, water systems, heat management, urban ecology, etc are all important factors in rainfall management but these issues often extend outside any one city governmental department. The differing bureaucratic structuring as well as laws and regulations can make monitoring and implementing designs more difficult. For example, consider NYC street trees; the city parks department is responsible for the tree while the property owner is responsible for the tree bed and the utility company is responsible for changes that encroach on their jurisdiction (Columbia 2018). Additionally, one considers the transportation department during adjacent street repairs or the mayor's office for setting management goals, etc. The complexity of governance creates confusion and limits the potential effectiveness of policy.

By reorganizing city agencies to better handle water management, flood management and disaster response, cities would eliminate confusion of policies between agencies and help streamline future policy. Paired with the continued and easily accessible guiding policy documents, civil servants and citizens would be more able to cross fields and engage with each other to achieve the common goal of mitigating against flooding from rainfall. Pluvial flooding can be more deeply integrated into emergency planning to handle inconveniences like traffic rerouting or localized property damage but can also prepare first responders and citizens to manage large scale flooding that suspend services and threaten human health and wellbeing. The policy alternative of government streamlining allows for the city to better focus their policy goals, enact change and prepare for the future.

1.4.5 Maintaining Urban Environments

The final of the five policy alternatives is maintaining the existing urban environment. This policy alternative consists of an assortment of actions for protecting infrastructure, removing blockages and mitigating flood damages. Street litter management, land use planning and citizen education are fundamental steps in this alternative. Again, there is disagreement between the cities in the discussion rates of this alternative. Auckland has the highest focus on this (64%) mostly due to their commitment to managing urban sprawl and the rural environment (Table 2). On the other hand, NYC has the lowest discussion rate at 36%. This alternative also has the lowest average discussion rate across the six cities, roughly 44%. This is not to say that NYC and the other cities do not utilize this alternative but rather that this alternative is not directly discussed and may be integrated into other areas of city management or masked by other initiatives.

Firstly, cities can manage the amount of litter on the street to prevent blockages to existing grey and green infrastructure. From street sweeping programs to littering campaigns, taxes, bans and educational campaigns, cities need to ensure that their stormwater system operates efficiently. Catch basin management also ensures that coastal environments can continue to effectively process rainwater. While the cities touch on this, these actions are usually grouped under waste management and not viewed as specific solutions to pluvial flooding. This lack of definition limits the cities' discussion of this alternative. Yet, if the existing infrastructure can handle capacity it is important to make sure they run smoothly without blockages.

More directly, cities can manipulate the urban environment to protect against pluvial flooding with land use management. Land use planning dictates urban form and thus how cities must develop responses to problems. However, while urban sprawl remains a problem for the cities' regions, the cities themselves, with the notable exception of Auckland, are more concerned with intensive urban development Thus, urban growth does not remove large amounts of natural environments or parkland, limiting the explicit discussion of this alternative. However, providing guidance for concentrated growth is still important and fits nicely within land use strategies for coastal and fluvial flooding protections. Maintaining urban environments is the hardest alternative to identify as it easily blends into other areas of city management yet is important in ensuring that city systems function efficiently.

1.4.6 Summary of Alternative Conditions

As all five policy alternatives are currently present within the six cities, it demonstrates that city governments have the existing funding mechanisms, technical skills and abilities to implement the alternatives. However, each alternative comes with different requirements; Table 1.4 provides an overview of these characteristics. While each alternative can develop with time, they are currently not dependent on any future technical or political developments and are ready to be implemented. Each of the alternatives discussed above represent a general typology of alternative and are not specific to an exact solution i.e. green roofs or a storm drain cleaning campaign. Therefore, it is difficult to summarize exact quantitative values as identifying definitive values is highly dependent on location, scope, area size, labor, materials, etc. which vary within a city and across the cities. In a site specific study, it is imperative to collect these estimates when selecting an alternative, but here this research summarizes the expected types of requirements to consider.

Table 1.4: Summary of characteristics of the five policy alternatives

Policy Alternatives	Characteristics
Public Green Infrastructure	**Cost**: Construction costs and lifetime management costs. Often specialized materials and labor. Management can be stewarded out but some level of expected government oversight. **Lifespan**: Variable depending on type but within similar ranges of existing options today, sometimes slightly longer than previous grey infrastructure. **Water Volume**: Dependent on if the purpose is to store or delay. 'Delay' options have variable flow rates but have a final saturation volume. 'Store' options can be constructed for a larger capacity. **Benefits**: Additional urban green spaces, connections to other hazards (i.e. heat), biodiversity, connections to sustainability. **Tradeoffs**: Can require rezoning, subject to public approval, limited to public lands.
Private Green Infrastructure	**Cost**: Construction and maintenance costs borne by private citizens. **Lifespan**: Variable depending on type but within similar ranges of existing options today, sometimes slightly longer than previous grey infrastructure. **Water Volume:** Dependent on if the purpose is to store or delay. 'Delay' options have variable flow rates but have a final saturation volume. 'Store' options can be constructed for a larger capacity, but limited space on private land hinders larger projects. **Benefits**: Lowered utility bills for private citizens, benefits of additional urban green spaces, fill in the gap of public infrastructure. **Tradeoffs:** Loss in public tax revenue from offering incentives, dependent on willingness of private citizens.
Grey Infrastructure Overhauls	**Cost**: Construction cost and lifespan maintenance costs. Often drawing from an existing funding, skills and labor market. **Lifespan**: Variable but materials development has increased lifespans from previous projects. **Water Volume**: Can be built for required water volumes. **Benefits**: Most familiar to implement. **Tradeoffs**: Subject to public approval, disruptive public works.
Government Streamlining	**Cost**: Dependent on the scope of reorganization. New agency construction/new hiring or delegating new roles to existing positions. Publication and information campaign costs. **Lifespan**: Not applicable. **Water Volume**: Not applicable. **Benefits**: Increases transparency in governance, increases management of stormwater and flooding resources.

	Tradeoffs: Redirection of limited governmental funds to a new area of focus.
Maintaining Urban Environments	**Cost**: Dependent on scope, usually in the form of campaigns and employment. **Lifespan**: Not applicable. **Water Volume**: Help ensure existing capacity is maintained. **Benefits**: Cleaner urban environments, better informed citizens, potential for reduced pollution. **Tradeoffs**: Long time span to see behavioral changes.

Source: The table is summarized from the documents found in Table 1.1 and 1.2

There is a range in requirements across the alternatives. Considering cost, the three infrastructure alternatives have more fixed costs whereas the two management alternatives are more scalable in their funding abilities. Regardless of the initial costs, all alternatives require some form of longer-term maintenance funding. The lifespan of an alternative also varies, with the infrastructure alternatives having set lifespans while the management alternatives can be stopped and started whenever required, however, this leaves them at the mercy of funding availability within municipal governments.

Importantly, only the infrastructure alternatives can increase stormwater volume capacity. Yet this is only feasible when capacity for storing stormwater is not overwhelmed by rainfall totals, in which case even these infrastructure types might overload their capacity. The two management alternatives do not increase capacity and only maintaining urban environments directly enforces existing capacities. While the benefits have been largely summarized in sections 1.4.1-1.4.5, all five alternatives carry some level of tradeoff. This is not a definitive list of tradeoffs but represents major concerns when selecting an alternative. The infrastructure alternatives always require some form of public approval in a democratic city and are thus subject to a lengthy planning and construction process. While the management alternatives are quicker to implement, their benefits might be slower to emerge and can redirect funding from other pressing urban issues.

1.4.7 Additional Cities

The same five policy alternatives are all present in the policy documents from the additional six cities in North America, Australasia and Europe. Additionally, there are some similarities in the discussion rates of the alternatives (Table 1.5). While each

Table 1.5: Discussion rates of the five policy alternatives within the six additional case cities

	Grey Infrastructure Overhauls	Public Green Infrastructure	Private Green Infrastructure	Government Streamlining	Maintaining Urban Environments
Boston (*n*=6)	67%*	100%	50%	33%*	50%
San Francisco (*n*=7)	57%*	100%	29%*	29%*	29%*
Wellington (*n*=7)	57%*	100%	14%*	14%*	43%*
Brisbane (*n*=7)	71%*	100%	71%*	43%*	57%*
Oslo (*n*=7)	14%*	100%	43%*	57%*	29%*
Dublin (*n*=6)	83%*	83%*	50%	50%	67%*

*Rounded value

city may utilize their own mix of the alternatives in the guidance policies, each alternative is a welcome adaptation method across the developed regions.

All six additional cities have on average stronger discussion rates of grey infrastructure overhauls and public green infrastructure over the other alternatives. However, in these cities grey infrastructure is discussed at a lower rate than in the original six cities. Particularly, Oslo only references grey infrastructure at 14%. Oslo was recently the 2019 European Green Capital and thus their documents emphasize a movement towards greener solutions. Nonetheless, each city continues to reference the alternative underscoring the importance of retrofitting the existing urban stormwater infrastructure within developed cities to manage future pluvial flood events.

Public green infrastructure is confirmed to be highly discussed in the developed cities. This coincides with the results of the original six cities, and that there is an emerging rhetoric and emphasis on green and sustainable solutions through visual public infrastructure projects managed by the city. Additionally, private green infrastructure is discussed at lower rates than public projects and private green infrastructure is discussed on average less in the additional cities than the original. Furthermore, there is no dominance by the European cities in private green infrastructure. Boston, for example, exhibits a higher discussion rate of private green infrastructure than Oslo. However, all the cities recognize the importance of using private green infrastructure to ensure a comprehensive urban green network.

Finally, government streamlining and maintaining urban environments are not as strongly discussed when compared to the other alternatives. However, the additional six cities recognize that these alternatives can be useful in pluvial flood management, but the specific policies might be masked by other initiatives or not explicitly discussed.

The additional six cities confirm that the five policy alternatives are not unique to the original six case cities. Furthermore, they demonstrate that there is a similarly high trend in discussing both public green infrastructure and grey infrastructure overhauls across the twelve cities. Cities are discussing policy alternatives towards a greener future without ignoring the existing infrastructure they have and knowledge base to draw from.

1.5 Chapter Conclusions

The six cities this chapter presents are expected to receive higher intensity rainfall events due to climate change regardless of changes in rainfall totals. These cloudburst events can inundate local areas, overwhelm stormwater infrastructure and lead to economic and social damages in the cities. City leaders and planners can use policy to begin mitigating the effects of pluvial flooding and enhance the sustainability of the urban environment.

The five policy alternatives presented are fundamental in each city’s management strategy. These alternatives are not a comprehensive list of management styles but rather consistent options that cities discuss in their guiding policy documents. Each city uses all the five alternatives convergently as in practice these alternatives are rarely alone but rather as a supportive network of alternatives to help against pluvial flooding. The city specific strategies are also a product of local environmental and historical factors. Nonetheless, grey infrastructure and public green infrastructure remain the dominant of the two alternatives while there is less consensus among the other three; public green infrastructure, government streamlining and maintaining urban environments.

NYC, Vancouver, Sydney, Auckland, Copenhagen and Amsterdam present differing narratives towards pluvial flooding. The European cities craft a unique policy narrative of being innovators and pioneers in rainfall management. From the creation of cloudburst strategies and separate rainfall industries, paired with their high use of grey, private and public green infrastructure, the European cities take a very intensive approach to stormwater management. The inclusion and expectation of personal responsibility of the citizens also places the European cities in a unique position of moving the culture of sustainability and environmental responsibility further.

The North American cities do not present a unified vision of stormwater management. Alongside efforts to incorporate sustainable and environmental management into the stormwater management network, NYC remains a large city of competing interests with comparatively lower discussion rates of the alternatives. On the other hand, Vancouver has embraced an image of environmental friendliness and constructs a narrative of rainfall management full of 'green' improvements. However, with a mix of alternative discussion rates, Vancouver is flexible on how to achieve their management goals and not dedicated to one method.

In Australasia, the city management differences are reflected in the fundamental environmental problems; Sydney is too dry, and Auckland is too wet. While Auckland focuses on protecting the natural environment and landscape, Sydney is focused on ensuring water security. Beyond grey and green infrastructure, the cities again differ in the discussion rates of the different alternatives to management, reflecting the differences in their needs.

While only a small subset of developed cities across the three regions, the alternatives to adaptation and the subsequent trends in the discussions around these alternatives are found in an additional six cities from the same region: Boston, San Francisco, Wellington, Brisbane, Oslo and Dublin. The alternatives are adaptation measures that cities are looking to regardless of their needs and narratives for stormwater adaptation.

The lessons these cities demonstrate are useful for other policy makers. In other developed cities the message is clear; expanding infrastructure to handle stormwater is not just about stormwater pipes anymore. The six cities are changing their urban environments into absorbent landscapes both with new stormwater designs and through retrofitting existing systems. There is a large focus on the ideas of a green and sustainable urban future but an admittance on the importance of the existing structures. There are lessons for developing cities as well. Solutions for stormwater management do not need to answer just stormwater. With an opportunity to build new systems, developing cities can embrace the co-benefits of green spaces and streamlined urban management to address multiple problems at once. It is not possible to replicate a city's response in another but these six cities and their resources present ideas in best management practice.

The following chapters discuss how the cities reach these policy decisions. This includes examining the role different stakeholder groups have in the formulation of policies and the choice of alternatives. Researchers, civil servants and the public all influence how policy is developed. Additionally, the chapters evaluate the criteria for making a policy decision regarding cloudburst stormwater management and how the alternatives perform alongside these criteria preferences. As climate change increases, understanding what is valued in the policy can guide future decisions. This chapter presented a comprehensive exploration of what policies six developed cities utilize in managing heavy rainfall events and how their policy narratives focus on different arrangements of five varying management alternatives.

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Appendix 1.1: Multi-Dimensional Scaling

The following chapter appendix demonstrates the results of the Multi-Dimensional Scaling analysis for the selection of the case cities. The analyses apply classical MDS or principle component analysis (Gower 1966). K-means are then applied to demonstrate city clustering. The number of clusters are justified with the ‘elbow method’ to determine the within-cluster sum of squares to identify the optimal number of clusters and where necessary the ‘silhouette’ method to identify the quality of the clustering.

The initial analysis focuses on the two demographic and two economic indicators with three clusters identified (figure A1.1.1). As the majority of cities were concentrated in cluster 2, the analysis was re-run focusing just on cluster 2 (figure A1.1.2). The elbow method of determining cluster suggest that the remaining twenty-five cities can be clustered into four groups, with the silhouette method suggesting that while this is a good quality of groups, other numbers of clusters may be similarly satisfactory and the four clusters are not strongly unique.

When the additional two environmental indicators are added there is very little change to the resulting MDS plot and groups and when the two economic indicators are removed from the analysis, the MDS produces the same clusters as the initial analysis (figure A.1.1.3). Regardless of the indicator data, the second cluster contains the same majority of cities. Due to the difficulty in identifying city clusters, the thesis proceeds with six geographically spread cities; however, of note New York City is from one of the three clusters, Auckland from another with the remaining four cities from the largest cluster.

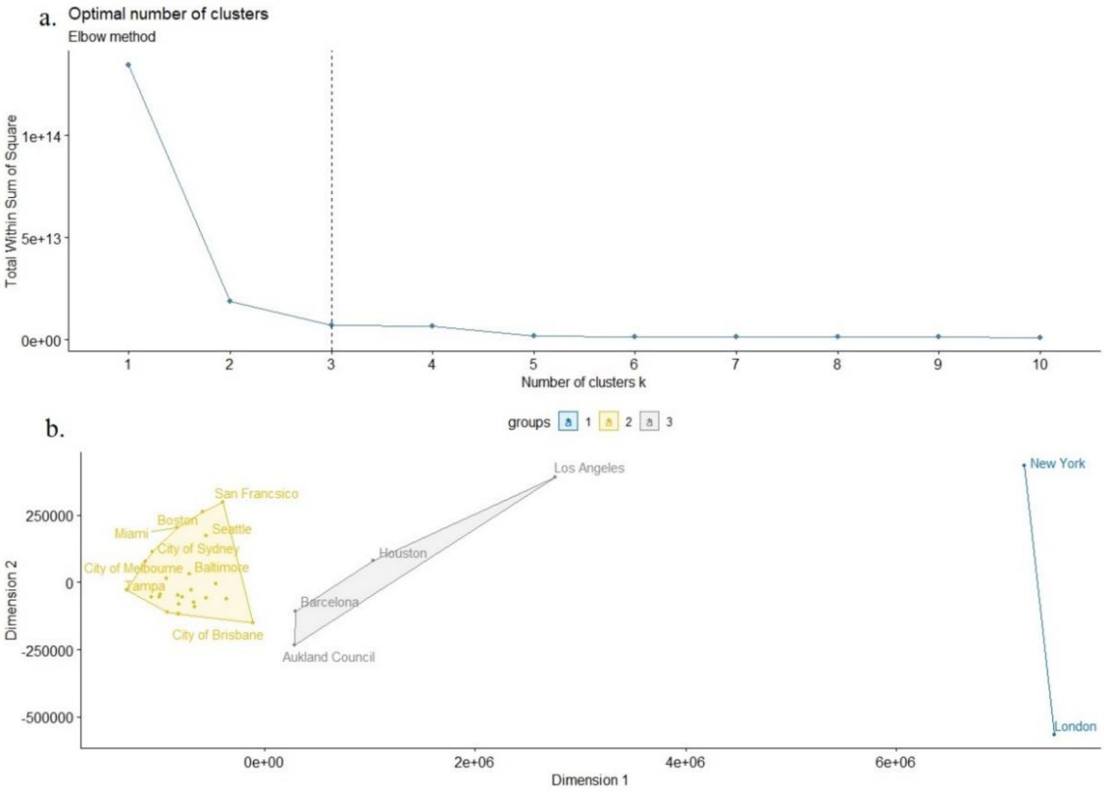

Figure A1.1.1: a. The optimal number of clusters for the 31 cities and their demographic and economic indicators using the elbow method and b. the resulting three clusters

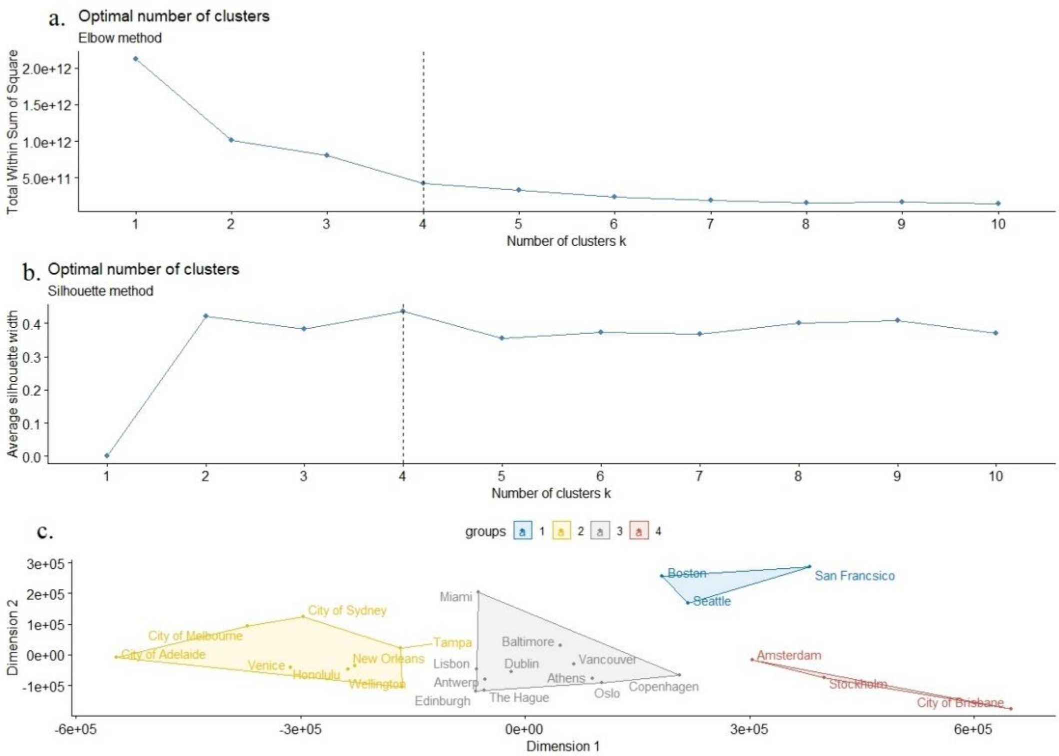

Figure A1.1.2: a. The optimal number of clusters for the remaining 25 cities and their demographic and economic indicators using the elbow method, c. justifying the clusters with the silhouette method and c. the resulting four clusters

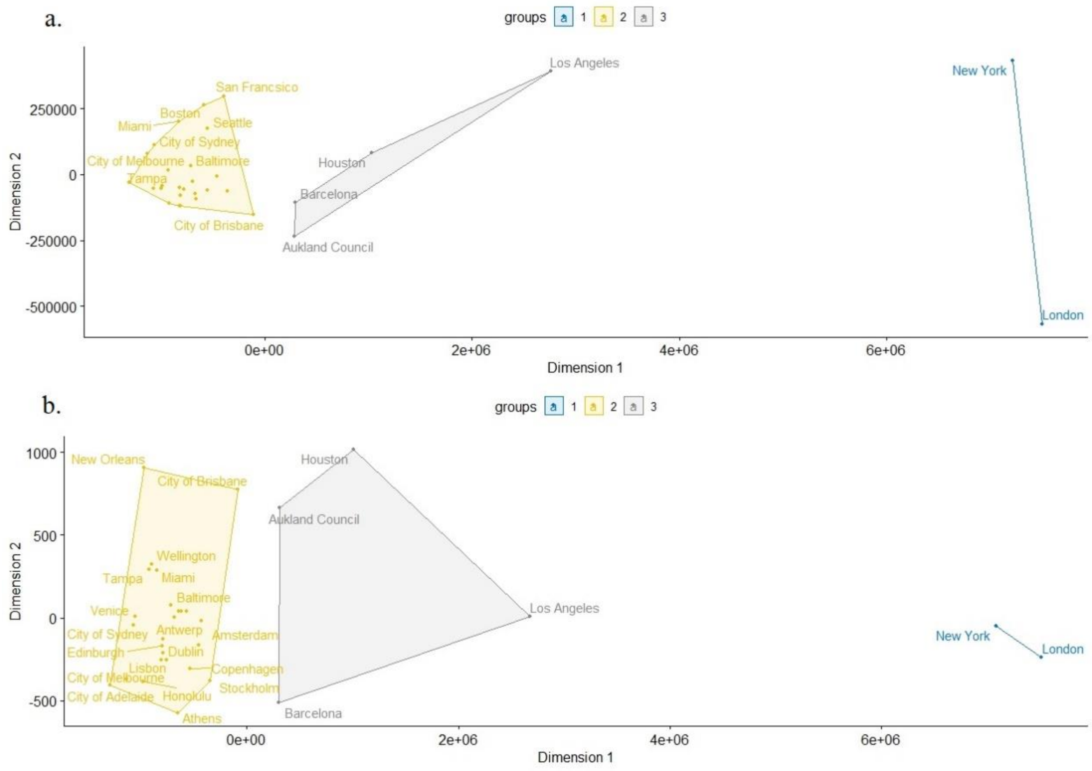

Figure A1.1.3: a. The three clusters of the 31 cities considering the demographic, economic and environment indicators, and b. the three clusters of the 31 cities considering the demographic and environmental indicators

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Chapter 2: Implementing an AHP-TOPSIS Multi-Criteria Decision Analysis method for Stakeholder Integration in Urban Climate and Stormwater Adaptation*

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2.1. Introduction

Climate change is placing enormous pressures on urban policy decision making. Traditional governance decision-making methods are being re-evaluated with the growing importance of urban sustainability, resilience and adaptation. While disruptive of the status quo, this shift allows cities engage with different and larger groups of people and concepts than before.

What defines urban climate adaptation is that decisions need to be made quickly for both long-term and immediate threats, at varying geographic scales, alongside varying climate projections. Urban pluvial flood management exemplifies these difficult considerations. For long-term adaptation, projects become stalled as the main benefits from implementation are often reaped decades later providing no or limited immediate financial returns (Antrobus 2011). With how environmental benefits are usually quantified, it is an uphill battle to pursue future environmental investments over other im-mediate pressing urban issues. The idea of future proofing is also questioned as technologies may become obsolete or climate projections over or underestimate the future reality (Qi *et al*. 2020).

For immediate threats, urban bureaucracy still poses a barrier to adaptation. It is not a lack of best practice awareness that delays policy but rather policy systems are not designed for radical changes (Henstra *et al.* 2020). Policy makers become familiar with certain methods and processes and may struggle to diverge from this path dependence in the face of emerging pressures (Matthews *et al.* 2015). Furthermore, communication and coordination be-tween departments may not be streamlined despite the interdisciplinary effects of climate change. As these delays compound across the various levels of governance, policy making may struggle unless radical change occurs.

Despite the barriers, cities are making progress incorporating climate adaptation into their decision-making framework. Environmental considerations are becoming commonplace within governance (Aylett 2015). However, as with most policy a city needs both strong political systems and political will to support environmental policy (Qi *et al.* 2020; Czako 2013). Cities must increase their efforts to streamline policy guidance across their often-segregated departments and coordinate regulations across sometimes unresponsive state/regional and national governance. Without this inter and intragovernmental support, the adaptation decision-making process becomes more difficult (Aylett 2015). Existing governance structures may not be the best suited for the complex decisions climate change requires.

Urban climate adaptation decision-making should involve many stakeholders. While every citizen will be affected by climate change, it is unrealistic to include everyone in this process. Therefore, cities must be careful to select relevant stakeholders to the decision (Andre *et al.* 2012). When defining the scope of the decision, the outcome must be applicable to the relevant stakeholders so finding a balance between inclusion and decision relevance is highly important in adaptation processes.

Relevant stakeholders often hold conflicting views further complicating decision-making. The perceptions towards adaptation solutions are often based in existing knowledge and experiences (Qi *et al.* 2020; Gallo *et al.* 2020). Additionally, issues around the environment and climate change bring conflicting definitions, emotion and uncertainty into the process. While green infrastructure mimicking natural process, and more specifically blue-green infrastructure concerning stormwater management, emerge as best practices, what constitutes green solutions can differ between groups and the multi-faceted aspects of these adaptation solutions creates differing perspectives in best management practice (Torabi *et al.* 2021; Matthews *et al.* 2015). As climate change projections adjust, the relevance of stakeholders may also need to adjust. The inclusion of different people in decision-making is imperative for successful decisions but adds a layer of complexity to the process.

Regardless of the complexity of climate change, urban decision-making and adjusting governance systems, cities continue to make adaptation decisions. Considering urban stormwater and the results of Chapter 1, theory indicates that rainfall intensity will increase in urban areas and best management practice is moving towards blue and green solutions (Axelsson *et al.* 2020). However, these solutions require multi-criteria considerations and involve stakeholders outside of formal stormwater management (Pakfetrat *et al.* 2020). Particularly, purely valuing green infrastructure in economic terms might influence its acceptability for a given decision (Locatelli *et al.* 2020). Considering this, this chapter aims to demonstrate that a multi-criteria decision analysis (MCDA), based on a combined Analytic Hierarchy Process (AHP)- Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS) method, can contribute to increased stakeholder involvement and satisfaction with urban stormwater adaptation policy. While these methods have been utilized in stormwater management before, they are usually presented with a level of expertise that prevents non-experts from immediately engaging with the methodology. Additionally, the method allows for the quantification and analysis of differences between stakeholders in urban decision-making allowing for policy makers to analyze these differences and create more inclusive policy, something that previous studies have not thoroughly explored. The method is demonstrated with a case study from New York City (NYC).

2.2. Multi-Criteria Decision Analysis

MCDA tools are useful for policy makers to visualize, quantify and increase transparency in the decision-making process by helping to evaluate the criteria influencing the decision and the possible decision alternatives to implement. Multi-Attribute Utility Theory (MAUT), Simple Multi-Attribute Rating Technique (SMART), AHP, Case Based Reasoning (CBR), Simple Additive Weighting (SAW), TOPSIS, Elimination et Choix Traduisant la Realite (ELECTRE) and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) are some of the MCDA methods that have been successful utilized in environmental decision making (Guarini *et al.* 2018; Velasquez and Hester 2013). Each method is optimized for different types of data, required complexity of analysis, uncertainty levels, computational intensity and experience of the decision maker. Ultimately, there is no single best MCDA method for making decisions (Pakfetrat *et al.* 2020; De Montis *et al.* 2000; Guitouni and Martel 1998). While it may be possible to evaluate different methods for a specific challenge, the ability to identify an optimal method is hindered when there is low knowledge of MCDA methods amongst the decision makers (Guarini *et al.* 2018).

In climate change decision making one selects an MCDA method based on preference and perceptions of what best fits the data and can represent the requirements of the decision. Nonetheless, it is still crucial to be critical when selecting an MCDA method as it will affect the output of the criteria, alternatives and eventual decision (Pakfetrat *et al.* 2020; Guarini *et al.* 2018). It is important to understand the method used, and how easy it is for stakeholder involved in the decision-making process to understand the method. Participants need to understand the alternatives and the criteria to conceptualize the influence their judgments will have on the decision process (Steele *et al.* 2009). While it is the decision analyst's responsibility to make sure the participants understand the alternatives and criteria, they must also be transparent in the process. A decision aid such as computer programing, forms and surveys makes the process more transparent. MCDA methods ultimately exist to aid making complex decisions and attention should be taken when selecting the appropriate method for the given problem.

This chapter introduces using a combined AHP-TOPSIS MCDA method for stormwater management adaptation. The AHP developed by Saaty (1980) is a linear model based on pairwise comparisons while TOPSIS developed by Hwang and Yoon (1981) is a compensatory method measuring the distance to an idealized solution. In this method, the AHP is used to develop the weights of the criteria and sub-criteria in the decision-making process. As the number of criteria needed in urban policy and climate change decisions becomes complex, the criteria weights are then utilized in TOPSIS to test the performance of the alternatives, reducing the number of judgements required by the decision-maker and the computational complexity of the MCDA. The strength of this method is that conceptually and mathematically it is easy for non-experts to engage with while being robust and accepted in the field. While other methods additionally reduce the computational burden on largescale pairwise comparisons, they often become complex for non-expert communities (Fedrizzi and Giove 2013; 2007). The method proposed here is appropriate as it is approachable for various stakeholders involved in urban climate adaptation decisions. Additionally, the method allows the decision-maker to observe how different stakeholder value different criteria and policy alternatives.

The AHP is a robust tool because of its ability to handle stakeholder involvement, integration of qualitative judgements and legacy in the fields of policy, governance and planning (Velasquez and Hester 2013). The AHP can directly engage with public officials familiar with the process over other MCDA methods as it is widely used. In addition, the method can easily be described to non-experts.

The AHP is capable of handling large amounts of qualitative data, important in urban environmental and climate change studies. When a large number of stakeholders with different interests are involved, the AHP allows for deep analysis of these differences (De Montis *et al.* 2005). This is critical when considering the integration of expert and non-expert stakeholders in decision making. For human judgement, the optimal amount of information a person can process, particularly during the AHP is 7 ± 2 judgements (Saaty and Ozdemir 2003). If environmental judgements become too complex, particularly with multiple comparisons an additional MCDA method can be used in conjunction. TOPSIS can integrate the criteria weights of the AHP to analyze the performance of the alternatives.

TOPSIS is based in finding an ideal alternative and measuring the distance performance of the alternatives from this. It allows for the direct comparison between cost and benefit type criteria, another importance in environmental decision making. While acknowledging the emergence of applying the fuzzy sets theory to the AHP and TOPSIS to compensate for inherent uncertainty in climate related decisions, due to the additional computational complexities and continued theoretical debate the method proceeds with the non-fuzzy calculations.

Table 2.1 displays recent studies from the past decade involving both the AHP and TOPSIS methodologies in a stormwater management context. These two MCDA methodologies are well established with stormwater management and have been applied to both large- and small-scale studies, with different national contexts, management alternatives and criteria considerations. However, there are two important gaps that exist in the literature. First, it is difficult to approach the mechanics of these methods without prior familiarity with the MCDA methodologies. Additionally, many of the studies involving AHP and TOPSIS include additional computational modelling, particularly Storm Water Management Model (SWMM). While acknowledging the role these MCDA methods can have within policy formation, it is difficult for non-technical experts, many of which are still highly important decision makers around stormwater management, to engage with the methodology. Without proper understanding of the

Table 2.1: Overview of literature on the AHP and TOPSIS MCDA methodologies in stormwater management

Study	Year Published	Description and Context
	AHP	
Young et al.	2010	The use of AHP in identifying stormwater management strategies in an American local municipality
Sahin et al.	2013	The use of AHP in identifying stormwater management strategies across councils in an Australian state
Siems and Sahin	2014	The use of AHP in identifying stormwater management strategies across councils in an Australian state.
Ebrahimian et al.	2015	The use of fuzzy AHP and compromise programing in stormwater collection systems in an Iranian urban context
Alhumaid et al.	2018	The use of AHP and PROMETHEE II in stormwater drainage system management in a Saudi Arabian urban context
Kordana and Slys	2020	The use of AHP to evaluate stormwater management strategies in at a building in a Polish context
Yu et al.	2021	The use of AHP in identifying optimal permeable pavement types for stormwater management.
	TOPSIS	
Jayasooriya et al.	2018	The use of TOPSIS to identify green infrastructure for stormwater management in industrial sites an Australian urban area
Hager	2019	The use of fuzzy TOPSIS to examine optimal stormwater management strategies in a Canadian context.
Luan et al.	2019	The use of TOPSIS to evaluate green infrastructure for stormwater in a Chinese sponge city
Zeng et al.	2021	The use of TOPSIS to identify green infrastructure solutions for stormwater management in a Chinese smart city
	AHP-TOPSIS	
Gogate et al.	2017	The use of AHP-TOPSIS to identify stormwater management alternative performances in an Indian urban area

Moghadas et al.	2019	The use of AHP-TOPSIS to evaluate flood risk in an Iranian urban area
Ekmekcioglu et al.	2021	Fuzzy AHP-TOPSIS for flood risk mapping in a Turkish municipalities
Koc et al.	2021	Fuzzy AHP-TOPSIS for stormwater management in a Turkish urban watershed.

methodology, the results of these methods can remain abstract to decision makers thus weakening their ability to trust or defend the methods' outputs when adopting policy for sensitive and uncertain decisions around climate change.

Second, the existing literature is focused on developing tools to find a solution to the stormwater issues the world faces while considering multiple stakeholders involved in the decision-making process. Aside from a few notable examples that consider differences between the stakeholders involved (Sahin *et al.* 2013; Siems and Sahin 2014; Ekmekcioglu *et al.* 2021), however, there is little focus on how to manage the differences in opinions and how this effects the end policy decision. If differences emerge between the stakeholders involved in the MCDA it is important to acknowledge these differences so that policy can then attempt to address the dis-parities. This is particularly important in stormwater management and climate change adaptation as many minority stakeholders might hold crucial viewpoints and local knowledge that are not typically examined by traditional policy making methods. It is important to consider the end goal of the MCDA but it is equally important to demonstrate how the AHP and TOPSIS methodologies can quantify stakeholder differences to allow for deeper policy discussions to occur around stormwater management.

Beyond MCDAs there are additional participatory decision tools or participatory modelling methods (PM). They range in computational intensity from less intensive decision tree analyses to more intensive fuzzy cognitive mapping (Kosko 1986) and system dynamic modelling. Additionally, there are tools that have specifically been applied to water management such as the Sustainable Procedure Framework (Hedelin 2016). However, similar to selecting an MCDA, there is no correct PM and the choice of PM is based on a set of factors such as available data, scope of the analysis, computational burden, time constraints and largely the previous experience of the decision maker and participants (Voinov *et al.* 2018). This chapter continues with the AHP-TOPSIS MCDA due to their aforementioned computational simplicity, ability to easily analyze stakeholder groups separately, widespread use of MCDAs and thus familiarity within urban policy and water management, and the widespread use of MCDAs in fields outside of governance thus increasing the chances of familiarity with non-expert stakeholders.

2.2.1. Criticisms

Two main technical criticisms are associated with the AHP and TOPSIS; rank re-versal and consistency. Rank reversal can occur when the addition of new or duplicate alternatives or the subtraction of an existing alternative can alter the final ranking of the alternatives (Wang and Luo 2009; Belton and Gear 1983). Rank reversal affects both the AHP and TOPSIS method (Keshavarz-Ghorabee *et al.* 2018; Garcia-Cascales and Lamata 2012; Wang and Luo 2009). The rank reversal phenomenon is largely a result of inconsistent judgements as well as internal aggregation and normalization methods during the analysis (Fedrizzi *et al*. 2018). To reduce the opportunity for rank reversal and maintain the internal mechanisms of the two MCDA methods, it is important to establish the independence of each alternative to avoid judgmental overlap or interdependencies. Furthermore, it is established that the AHP performs better when there is a small number of alternatives and many criteria (Guarini *et al.* 2018; De Montis *et al.* 2005). This additionally works for TOPSIS as the alternatives should be as unique and independent from one another so that the decision-maker examines the alternatives objectively and does not account for linked interdependencies in their judgments. Rank reversal in TOPSIS can further be reduced when the ideal solutions are predetermined and not reliant on the input data. The criteria should also be as independent as possible, but because they can be grouped together in sub-criteria categories, more similar criteria can still be judged objectively under a common criterion. Rank reversal is a common occurrence in both AHP and TOPSIS but in establishing a well-defined and independent set of alternatives it minimizes the chance of rank reversal with the introduction of new information.

The second criticism, consistency, influences the AHP method more than TOPSIS. There is debate over how much inconsistency or flawed judgements stemming from human decisions the AHP can tolerate. However, as Saaty, Vargas and Whitaker (2009) argue, issues regarding the AHP arise from the need to validate MCDA methods. The AHP is structured to handle the uncertainty of personal judgements and decisions without clear definitions and the results should be discussed within the context of the

AHP method. While these criticisms can influence the AHP-TOPSIS methodology, the method can be designed to minimize the influence of these drawbacks.

2.3. The Combined AHP-TOPSIS Methodology

An MCDA is generally performed in five stages (Figure 2.1) where we outline the proposed AHP-TOPSIS method through these stages.

2.3.1. Defining the Problem

The most important stage of any MCDA is to understand the nature of the problem. Like most decision making it involves defining the problem, geographic area, pressures on the problem and for whom and what a solution is needed.

2.3.2. Identifying the Criteria, Alternatives and Stakeholders

The criteria represent the factors of the decision and the alternatives are the potential solutions to the problem. Frequently, the criteria are derived from experience in decision making, while the alternatives are developed from the literature (Russo and Camanho 2015). While not a hard rule, it is generally preferable to verify the criteria and alternatives with experienced stakeholders or previous materials to ensure the relevance of the MCDA.

The stakeholder analysis identifies the parties relevant in the formation and implementation of policy and is integral in environmental decision making as it helps make the decision more robust and it can adapt the decision to local characteristics (Reed 2008). Stakeholder analyses are not just useful for environmental management

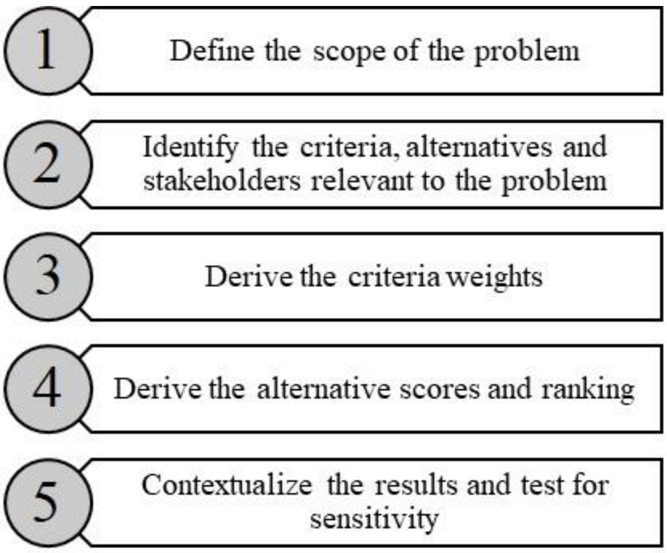

Figure 2.1: Stages of an MCDA analysis

but are frequently used across decision areas effecting cities (Reed *et al.* 2009; Reed 2008; Brugha and Varvasovszky 2000). However, a stakeholder analysis may not capture every relevant voice and can obscure minority voices and unexpected stakeholders (Reed 2008). Ultimately, who is included and who is excluded is based on the methods used.

A simple stakeholder analysis for decisions that need to be made quickly is the interest-influence matrix to categorize the stakeholders. Participants in the analysis list stakeholders and rate their interest and influence in the decision and if desired, offer comments on the relationships between the groups (Vogler *et al.* 2017). The stakeholders are then categorized into the four quadrants: high-interest/high-influence, high-interest/low-influence, low-interest/high-influence, and low-interest/low-influence and stakeholders can be selected as representative groups for participation in the MCDA.

No stakeholder method will be perfect in identifying everyone relevant towards the decision. As a top-down approach and depending on the participants, the interest/influence method can often identify usual stakeholders in the decision-making process and is also biased towards the opinions of those making the decision and rating the stakeholders as well as assuming how they judge other stakeholders is relevant (Reed *et al.* 2009). However, other bottom-up methodologies like stakeholder-led categorization and Q as well as additional methods such as social network analysis can be time intensive and are also subject to their own flaws. There is no perfect stakeholder analysis method and ultimately every stakeholder will not be captured by the methods. However, with well-defined scopes and limitations the interest/influence method can be quickly implemented as part of the integral stakeholder for the decision-making process.

2.3.3. *Weighting the Criteria and Scoring the Alternatives*

In this stage we employ the AHP-TOPSIS method. We determine the decision hierarchy of the problem to differentiate between the two MCDA methods (Figure 2.2).

2.3.3.1. *The Analytic Hierarchy Process for Criteria Weights*

First the AHP determines the criteria weights. In general, using pairwise comparisons one compares Criteria C_i with C_j to form a square matrix of dimensions $C_n x C_n$, matrix $A = [a_{ij}]$ (eq. 2.1). The matrix is reciprocal along the NW-SE axis.

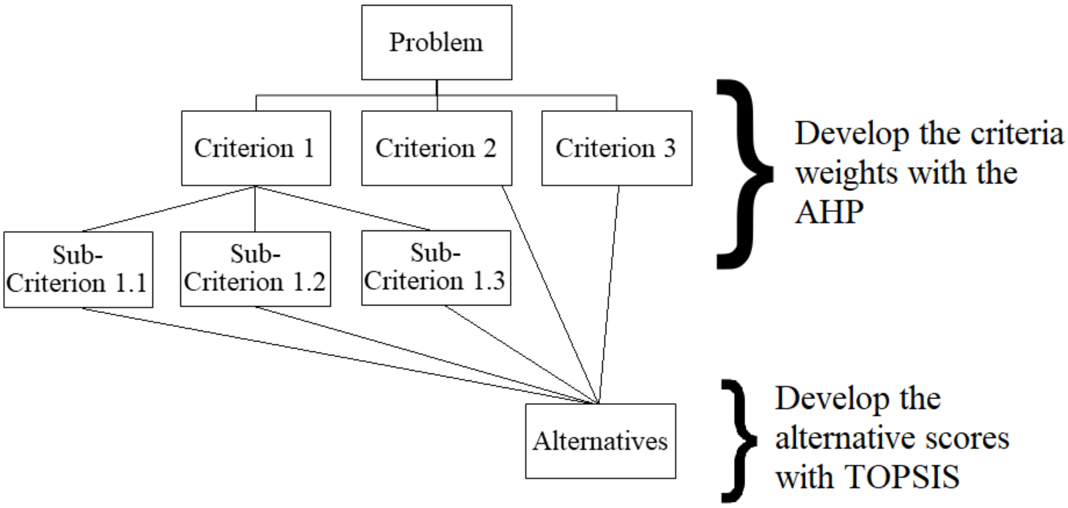

Figure 2.2: The AHP-TOPSIS MCDA decision hierarchy

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (2.1)$$

Where:

(i) $a_{ij} = \frac{1}{a_{ji}}$ for $i, j = 1, \dots, n$ and $i \neq j$

(ii) $a_{ij} = 1$ for $i, j = 1, \dots, n$ and $i = j$

The matrix is then normalized by matrix column to $\hat{A}$ (eq. 2.2).

$$\hat{A} = \begin{bmatrix} \hat{a}_{11} & \hat{a}_{12} & \cdots & \hat{a}_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{a}_{n1} & \hat{a}_{n2} & \dots & \hat{a}_{nn} \end{bmatrix} \quad (2.2)$$

Where:

$$\hat{a}_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

The pairwise comparisons between criteria are made using a linguistic scale, regardless of their quantitative or qualitative natures. Saaty’s original scale is linear from values 1-9 so that the difference between each successive value is proportional in magnitude (Table 2.2). While other scales exist the main difference between scales is how consistent a decision-maker performs in their comparisons (Goepel 2019; ISAHP 2018; Franek and Kresta 2014). Saaty’s linear scale is not the best at maintaining consistency, but it is still widely used and favored in practice (Franek and Kresta 2014; Zhang *et al.* 2009). Additionally, while different scales influence the criteria weights, they rarely influence the final ranking of the alternatives (Franek and Kresta 2017). Therefore, because of its integration in the non-scientific community, the method incorporates Saaty’s linear scale.

Table 2.2: Saaty's (1980) original linguistic and numeric scale for the AHP

Numeric Value	Description	Reciprocal Value
1	Equal Importance	1
3	Slight importance of one over another	1/3
5	Moderate importance of one over another	1/5
7	Very strong importance of one over another	1/7
9	Extreme importance of one over another	1/9
2, 4, 6, 8	Intermediate value	1/2, 1/4, 1/6, 1/8

Next, the priority weight vector is derived from matrix $\hat{A}$ that indicates the weight of each criterion in the matrix. Represented as $\boldsymbol{w}$, there are several methods of calculation. Saaty supports using the eigenvector of the matrix as the priority weight vector (Saaty 1990; 1980; Saaty and Vargas 1984). Alternatively, Crawford and Williams (1985) developed the logarithmic least squares or geometric mean method (GM) to determine $\boldsymbol{w}$. Minimizing the logarithmic error of the weightings, Barzilai argues the geometric mean method is unburdened by scale inversion and is better at handling optimization problems and error estimations (Barzilai 2001; 1998; 1997; Barzilai *et al.* 1992). To calculate the GM, $\boldsymbol{w}$ is derived from the geometric mean of the matrix rows (eq. 2.3). This method describes an explicit connection between matrix inputs and the weights allowing for a quick and effective sensitivity analyses (Brunelli 2015). Furthermore, this method remains simple regardless of the size of the matrix allowing for non-experts to quickly understand the process. Nonetheless, despite the ongoing theoretical disagreement over the optimal method to derive the priority weights, there are marginal practical changes on the end results when using both methods (Ishizaka 2004). Because of the GM's performance advantage as well as the direct connections to the input matrices and decision-makers ease of use, the method continues with the GM.

$$\boldsymbol{w} = \begin{pmatrix} w_1 \\ w_2 \\ \dots \\ w_n \end{pmatrix} = \begin{pmatrix} \sqrt[n]{\hat{a}_{11} \cdot \hat{a}_{12} \cdot \dots \cdot \hat{a}_{1n}} \\ \sqrt[n]{\hat{a}_{21} \cdot \hat{a}_{22} \cdot \dots \cdot \hat{a}_{2n}} \\ \dots \\ \sqrt[n]{\hat{a}_{n1} \cdot \hat{a}_{n2} \cdot \dots \cdot \hat{a}_{nn}} \end{pmatrix} \tag{2.3}$$

Where:

(i) $w_i > 0$ and $i = 1,2, \dots n$

(ii) $\sum_{i=1}^{n} w_i = 1$

There is an additional method of calculating the priority weight vector by using a combined weighting measure considering the AHP weights and an objective weight measure (Zhang and Wang 2021; Liu *et al.* 2020; Chuansheng *et al.* 2012). While these methods have not yet been widely adopted within the theoretical discussions around the

AHP, they are demonstrated to be good at removing the subjective and variable nature of the weights, thus reducing inconsistencies and the potential for rank reversals. However, they require an extra step of establishing the objective criteria hierarchy. In a case such as stormwater climate adaptation, a large volume of criteria may be difficult to analyze truly objectively, akin to the introduction of valuing ecosystem services within environmental economics. Furthermore, these combined methods work best when there is a high amount of accurate data regarding the alternatives and criteria (Al-Aomar 2010), something that is not always available in climate decisions with various projected outcomes. While these combined methods have promise in reducing the subjective nature of AHP weighting systems, they add an additional layer of technical complexity for decision makers while attempting to derive weights objectively with often variable and uncertain indicator data. Therefore, the method proceeds without a combined weight methodology.

Before the priority weight vector can be accepted, the decision matrix is tested for consistency. A consistency tests is important due to the nature of making subjective comparisons as well as the internal structure of the AHP. How one calculates the priority weight vector determines an appropriate consistency test.

Saaty (1980) developed a consistency index and ratio (CR) for the eigenvector method still widely referred to today in policy. In this measure, $\boldsymbol{w}$ is the eigenvector of the matrix so that λ would be the principle eigenvalue of the vector in accordance with the Perron-Frobenius theorem and $\lambda = n.$ Equation 2.4 demonstrates a relationship with matrix A assuming perfect consistency. However, because of inconsistency, Saaty proposes supplementing λ with the λ_{max} where $\lambda_{max} > n$ and the difference between λ_{max} and n is representative of the inconsistency of the judgements.

$$A\boldsymbol{w} = \lambda\boldsymbol{w} \tag{2.4}$$

Where:

(i) λ is the principle eigenvalue of matrix A

To allow the GM to be directly comparable with these existing eigenvector studies, the method incorporates the Geometric Consistency Index (GCI) interpreted by Aguaron and Moreno-Jimenez (2003) from Crawford and Williams (1985) (eq. 2.5). Here the GCI examines the “average of the squared difference between the log of the errors and the log of unity” (Aguaron and Moreno-Jimenez 2003: p.139).

$$GCI = \frac{2}{(n-1)(n-2)} \sum_{\substack{i,j=1 \\ i<j}}^{n} ln^2 e_{ij} \qquad 2.5$$

Where:

(i) $e_{ij} = a_{ij} w_j / w_i$ is the error obtained when the ratio $\boldsymbol{w}_i / \boldsymbol{w}_j$ is approximated by a_{ij}

Importantly, the GCI has a near linear relationship with Saaty's CR for CR<0.2 and for n≤4. One can take the equivalent GCI value and compare it directly with the CR. This is useful as the CR can represent a percentage and traditionally, if the CR<0.1 (10%), the comparison matrix is considered to have good consistency (Saaty 1980). However, a CR>0.1 does not mean that the matrix is necessarily invalidated, but critical attention should be paid to the decision matrix if it exceeds this amount. Therefore, sometimes a CR within 0.2 is still tolerable, particularly in uncertain areas such as climate change (Sahin *et al.* 2013; Wedley 1993). Here, the method accepts a CR<0.2 or a GCI<0.7052 (for n=4) when considering urban climate adaptation studies. If a matrix has a greater GCI, then the analyst must either disregard the matrix or ask the decision maker to re-evaluate their judgements. The GCI is beneficial as it related to the GM method, directly comparable with the CR and easy to conduct.

Equations 2.1-2.5 are repeated for each level of the hierarchy, i.e. a new matrix is constructed for each level of sub-criteria.

2.3.3.2. Group Aggregation of the AHP Weights

The method accounts for multiple stakeholders and thus the responses need to be aggregated together. Consistency can be used as a measure of aggregation (Farnia and Giove 2015; Barzilai 1998). Here the method incorporates the aggregation of individual priorities (AIP) where each decision maker produced their own $\boldsymbol{w}$ and GCI measure. The AIP method treats decision-makers as individuals allowing for their variation to be observed as opposed to the aggregation of individual judgements which treats decision-makers as a cohesive group aggregating them into one matrix (Carmo *et al.* 2013). Neither aggregation method is superior but depends on how to observe the decision-makers (Aragon 2017; Ivanco *et al.* 2017). Additionally, when using AIP should each decision-maker have acceptable consistency, the final aggregated $\boldsymbol{w}$ will be similarly acceptable (Saardchom 2012).

As the CR can be represented as a percentage, the method initially converts the GCI values to the equivalent CR. In practice, one cannot be more than 100%

inconsistent so we propose using a consistency measure (CM) as the inverse of the CR to demonstrate consistency (eq. 2.6). The CM can then subsequently be normalized by all the decision-makers to find the decision-makers' individual aggregation weight (aiw) (eq. 2.7). In a case where the decision makers display the same level of consistency, then an equal aiw would apply for all decision-makers.

$$CM^k = 1 - CR^k \qquad 2.6$$

Where:

(i) $k = 1, 2, \ldots, r$ for the set of decision-makers

$$aiw^k = \frac{CM^k}{\sum_{k=1}^{r} CM^k} \qquad 2.7$$

Where:

(i) $\sum_{k=1}^{r} aiw^k = 1$

The aggregated priority weight vector ($\bar{\boldsymbol{w}}$) for the entire group of decision-makers can be calculated using the weighted arithmetic or geometric mean. Both techniques do not violate the Pareto principle and are therefore viable (Ossadnik *et al.* 2016; Forman and Peniwati 1998). However, as the nature of the AHP relies on having ratio properties, the calculations proceed with the weighted geometric mean (eq 2.8) (Aragon 2017). Additionally, this method is less likely to be skewed by outliers in the data set (Ossadnik *et al.* 2016; Pauer *et al.* 2016; Forman and Peniwati 1998). Finally $\bar{\boldsymbol{w}}$ is normalized to $\hat{\boldsymbol{w}}$ (eq 2.9).

$$\bar{\boldsymbol{w}} = \prod_{k=1}^{r} (\boldsymbol{w}^k)^{(aiw^k)} = \begin{pmatrix} w_1^1 \\ w_2^1 \\ \ldots \\ w_n^1 \end{pmatrix}^{aiw^1} \cdot \begin{pmatrix} w_1^2 \\ w_2^2 \\ \ldots \\ w_n^2 \end{pmatrix}^{aiw^2} \cdot \ldots \cdot \begin{pmatrix} w_1^K \\ w_2^K \\ \ldots \\ w_n^K \end{pmatrix}^{aiw^r} = \begin{pmatrix} \bar{w}_1 \\ \bar{w}_2 \\ \ldots \\ \bar{w}_n \end{pmatrix} \qquad 2.8$$

$$\hat{\boldsymbol{w}} = \frac{\bar{w}_i}{\sum_{i=1}^{n} \bar{w}_i} = \begin{pmatrix} \hat{w}_1 \\ \hat{w}_2 \\ \ldots \\ \hat{w}_n \end{pmatrix} \qquad 2.9$$

Equations 2.6-2.9 are repeated to determine the group priority weighting of each decision matrix including each level of the hierarchy if sub-criteria are present. To condense the criteria and sub-criteria weights into the global aggregated weights of the criteria interacting with the alternatives in the decision hierarchy, one takes the weight of the aggregated parent criterion and multiplies it by the aggregated priority weight vector of the sub-criteria matrix (eq. 2.10). The final global aggregated weights of the criterion that interact with the alternatives is now presented simply as the final priority weight vector $\boldsymbol{w}$ (eq. 2.11).

$$\boldsymbol{w}_{global\ sub-criteria\ matrix} = \widehat{w}_i \widehat{\boldsymbol{w}}_{sub-criteria\ matrix} \tag{2.10}$$

Where:

(i) w_i is the weight of the parent criterion in the decision hierarchy from the aggregated parent priority weight vector

$$\boldsymbol{w} = \begin{pmatrix} w_1 \\ w_2 \\ \dots \\ w_n \end{pmatrix} \tag{2.11}$$

Where:

(i) w_j is the global weight of criterion j that interacts with the alternatives in the decision tree

(ii) $w_j > 0$ and $j = 1, \dots, n$

(iii) $\sum_{j=1}^{n} w_j = 1$

2.3.3.3. The Technique for Order of Preference by Similarity to Ideal Solution for Alternative Scores

After establishing the criteria weights, TOPSIS analyzes the performance of the alternatives. As the decision makers are considered a group in the AHP, the method continues using a group aggregation method for TOPSIS provided by Shih et al. (2007). In group decision maker, certain decision-makers may provide overly strong preferences and aggregation techniques might mask this dominance leaving other decision-makers dissatisfied with the outcome. While some aggregation techniques target this phenomenon specifically (Huang and Li 2012), Shih et al. (2007) demonstrate that their method is useful under different distance measurements and internal aggregation techniques.

Starting in TOPSIS, a decision-maker k rates the alternatives A_i to the criteria C_j in a matrix $B^k = [f_{ij}]$ of dimensions $A_m x C_n$ (eq. 2.12). The matrix is then normalized to matrix $Z^k = [z_{ij}]$ as the square root of the sum of the squared matrix input by column (eq. 2.13). Unlike in the AHP, in TOPSIS the decision maker is only constructing one matrix, reducing the required burden of judgements.

$$B^k = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{matrix} C_1 & C_2 & \dots & C_n \end{matrix} \\ \begin{bmatrix} f_{11} & f_{12} & \dots & f_{1n} \\ f_{21} & f_{22} & \dots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1} & f_{m2} & \dots & f_{mn} \end{bmatrix} \end{array} \tag{2.12}$$

Where:

(i) A_i represents the alternative i and C_j represents the criteria j, for $i = 1, \dots, m$ and $j = 1, \dots, n$

(ii) And f_{ij} represents the performance rating of A_i under C_j

(iii) For k=1,2,…,r for the number of decision-makers

$$Z^k = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{bmatrix} \qquad 2.13$$

Where:

(i) $z_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^{m} f_{ij}^2}}$

Quantitative values are directly input into the matrix while qualitative judgements are made using a linguistic scale. Like AHP, a 1-9 scale exists for TOPSIS judgements (Table 2.3). The analyst can establish many varieties of scales but in a stochastic TOPSIS, the 1-9 scale is satisfactory (Erdogan and Kaya 2019).

Table 2.3 A simple linguistic and numeric scale for TOPSIS

Linguistic Value	Numeric Value
Very Low	1
Low	3
Moderate	5
High	7
Very High	9

At this stage, Shih et al. (2007) differ from the traditional TOPSIS by delaying the addition of the criteria weights into the matrix until later in the process. The analyst now establishes the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS) for each criterion, or matrix column. The PIS (Z^{k+}) represents the best performing alternative value in the criterion (eq. 2.14) and the NIS (Z^{k-}) the worst performing value (eq. 2.15). The PIS and NIS are influenced if the criteria is considered a cost (preferred low value) or a benefit (preferred high value).

$$Z^{k+} = \{(Max\ z_{ij}^k | j \in J\ ), (Min\ z_{ij}^k | j \in J') | i = 1,2, \dots, m\} = \{z_1^{k+}, \dots, z_j^{k+} | j = 1,2, \dots, n\} \qquad 2.14$$

Where:

(i) J is associated with positive criteria or benefits while J' is associated with negative criteria or costs

$$Z^{k-} = \{(Min\ z_{ij}^k | j \in J\ ), (Max\ z_{ij}^k | j \in J') | i = 1,2, \dots, m\} = \{z_1^{k-}, \dots, z_j^{k-} | j = 1,2, \dots, n\} \qquad 2.15$$

Where:

(i) J is associated with positive criteria or benefits while J' is associated with negative criteria or costs

Once the PIS and NIS are established for each criterion, considering the aggregated group priority vector $\boldsymbol{w}$ derived during the AHP, the analyst can calculate the separation measure of each alternative to the ideals. The Euclidean distance is one of several distance measures that can be considered (Vega *et al.* 2014; Shih *et al.* 2007). However, despite the measure's shortcomings in capturing the interdependencies between alternatives, the Euclidean distance is the traditional measure that is still applied in TOPSIS and has strong integration into the existing policy framework. The separation distance from the PIS (S_i^+) and the separation distance from the NIS (S_i^-)for each alternative is then calculated (eq. 2.16; 2.17).

$$S_i^{k+} = \sqrt{\sum_{j=1}^{n} w_j\left(z_{ij}^k - z_j^{k+}\right)^2} = \begin{pmatrix} \sqrt{w_1(z_{11}^k - z_1^{k+})^2 + w_2(z_{12}^k - z_2^{k+})^2 + \cdots + w_n(z_{1n}^k - z_n^{k+})^2} \\ \sqrt{w_1(z_{21}^k - z_1^{k+})^2 + w_2(z_{22}^k - z_2^{k+})^2 + \cdots + w_n(z_{2n}^k - z_n^{k+})^2} \\ \vdots \\ \sqrt{w_1(z_{m1}^k - z_1^{k+})^2 + w_2(z_{m2}^k - z_2^{k+})^2 + \cdots + w_n(z_{mn}^k - z_n^{k+})^2} \end{pmatrix} \quad 2.16$$

Where:

(i) w_j is the weight of criterion j from the priority weight vector $\boldsymbol{w}$

$$S_i^{k-} = \sqrt{\sum_{j=1}^{n} w_j\left(z_{ij}^k - z_j^{k-}\right)^2} = \begin{pmatrix} \sqrt{w_1(z_{11}^k - z_1^{k-})^2 + w_2(z_{12}^k - z_2^{k-})^2 + \cdots + w_j\left(z_{1j}^k - z_j^{k-}\right)^2} \\ \sqrt{w_1(z_{21}^k - z_1^{k-})^2 + w_2(z_{22}^k - z_2^{k-})^2 + \cdots + w_j\left(z_{2j}^k - z_j^{k-}\right)^2} \\ \vdots \\ \sqrt{w_1(z_{i1}^k - z_1^{k-})^2 + w_2(z_{i2}^k - z_2^{k-})^2 + \cdots + w_j\left(z_{ij}^k - z_j^{k-}\right)^2} \end{pmatrix} \quad 2.17$$

Where:

(i) w_j is the weight of criterion j from the priority weight vector $\boldsymbol{w}$

Once the separation distances are calculated for each decision-maker, the group aggregated separation distances are calculated. The aggregation can be performed but with the geometric and arithmetic mean achieving similar results (Shih *et al.* 2007). Similar to the justification in the AHP aggregation, because the separation measures are achieved through ratings based on scales and the arithmetic mean's ability to be influenced by outliers, the method uses the geometric mean (eq. 2.18; 2.19).

$$\overline{S_i^+} = \left(\prod_{k=1}^{r} S_i^{k+}\right)^{1/r} = \begin{pmatrix} (S_1^{1+} \cdot S_1^{2+} \cdot \ldots \cdot S_1^{r+})^{1/r} \\ (S_2^{1+} \cdot S_2^{2+} \cdot \ldots \cdot S_2^{r+})^{1/r} \\ \vdots \\ (S_m^{1+} \cdot S_m^{2+} \cdot \ldots \cdot S_m^{r+})^{1/r} \end{pmatrix} \quad 2.18$$

$$\overline{S_i^-} = \left(\prod_{k=1}^{K} S_i^{k-}\right)^{1/r} = \begin{pmatrix} (S_1^{1-} \cdot S_1^{2-} \cdot \ldots \cdot S_1^{K-})^{1/r} \\ (S_2^{1-} \cdot S_2^{2-} \cdot \ldots \cdot S_2^{K-})^{1/r} \\ \vdots \\ (S_m^{1-} \cdot S_m^{2-} \cdot \ldots \cdot S_m^{K-})^{1/r} \end{pmatrix} \quad 2.19$$

In the final stage, the relative closeness to the ideal solution $\overline{C_i^*}$ is calculated as a measure of each alternative's separation from the ideal positive and negative solutions (eq. 2.20). The results are presented on a scale of 0-1 and the final ranking of the alternatives are listed in descending order.

$$\overline{C_i^*} = \frac{\overline{S_i^-}}{\overline{S_i^+} + \overline{S_i^-}} \quad 2.20$$

2.3.4. The Sensitivity Analysis

The sensitivity of the results of the AHP-TOPSIS analysis needs to be explored to understand how stable the results are. As uncertainty is prevalent in making subjective judgements, a sensitivity analysis demonstrated how reliable the results are given the criteria weights (Jiri 2019; Song and Chung 2016; Li *et al.* 2013). While many methods exist to examine sensitivity, the method incorporates Li et al.'s (2013) sensitivity test as it is computationally simple and its functioning is simple for non-experts to explore.

In general, a disturbance is placed upon one of the weights, w_q where q=1,2,3,…,n for the set of criteria in such w_q becomes $w_q^* = \gamma_q w_q$, where γ_q is the initial variation ratio of w_q and is >0. The sum of the weights must continue to equate to 1 so the weightings of the other weights are also adjusted by this variation (eq. 2.21).

$$\boldsymbol{w}' = \begin{pmatrix} w_1' = \dfrac{w_1}{w_1 + w_2 + \cdots w_q^* + \cdots w_n} = \dfrac{w_1}{1 + (\gamma_q - 1)w_q} \\ w_2' = \dfrac{w_2}{w_1 + w_2 + \cdots w_q^* + \cdots w_n} = \dfrac{w_2}{1 + (\gamma_q - 1)w_q} \\ \vdots \\ w_q' = \dfrac{w_q^*}{w_1 + w_2 + \cdots w_q^* + \cdots w_n} = \dfrac{\gamma_q w_q}{1 + (\gamma_q - 1)w_q} \\ \vdots \\ w_n' = \dfrac{w_n}{w_1 + w_2 + \cdots w_q^* + \cdots w_n} = \dfrac{w_n}{1 + (\gamma_q - 1)w_q} \end{pmatrix} \tag{2.21}$$

Where:

(i) w_1', w_2', w_q', and w_n' are the new weights for criteria 1, 2, q, and n after the disturbance of w_q

(ii) $\sum_{j=1}^{n} w_j' = 1$ and $j = 1, \dots, n$

β_q is the unitary variation ration of w_q after being altered and we can then represent γ_q in terms of β_q (eq. 2.22; 2.23).

$$\beta_q = \frac{w_q'}{w_q} \tag{2.22}$$

$$\gamma_q = \frac{\beta_q - \beta_q w_q}{1 - \beta_q w_q} \tag{2.23}$$

By establishing the parameter β_q, the analyst can test the variation of the weight on the criteria. For example, a β_q set at 0, 0.5, 0.8, 0.95, 1, 1.05, 1.20, 1.50, 2.00 would effectively be testing the variation of a criterion when the weight is adjusted by ±5%, ±20%, ±50% and ±100% while the other criteria are adjusted accordingly. The resulting shifts in the $\overline{C_i^*}$ for each alternative can easily be visualized graphically allowing the analyst to observe the ranking changes over the criteria weight changes. By testing each criterion, one can establish the criterion that is the most sensitive to the top-ranking alternative to change and the most sensitive to any alternative ranking to change.

2.4. The AHP-TOPSIS and New York City Stormwater Management

2.4.1. Study Area

NYC stormwater management under climate change provides an opportunity to demonstrate the effectiveness of the proposed AHP-TOPSIS method. As previously explored in Chapter 1, NYC is a large coastal city with roughly 8.5 million inhabitants. The city is a leader in regional, national and global leader in developing urban policy and can act as a case example for additional metropolitan areas to follow. Experiencing rapid growth in the 19th and early 20th century as well as several large public works projects in the mid-20th century, the city's urban stormwater infrastructure is ageing and needs to be adapted to the emerging precipitation pressures of climate change. Rainfall intensity is expected to increase within the city and the city has begun preparing adaptation measures. However, as with many large cities, complications in policy management arise as stormwater is a complex topic that overarches several city departments including Parks, Water and Planning with many non-governmental stakeholders also having a voice in the direction of policy management.

2.4.2. Defining the MCDA

Using the results of Chapter 1, the alternatives are defined as the five policy alternatives cities utilize in stormwater adaptation management: 1. Grey Infrastructure Overhauls, 2. Public Green Infrastructure, 3. Private Green, 4. Government Streamlining and 5. Maintaining Urban Environments

Using the same 58 policy documents from Chapter 1, Table 1.1, sixteen relevant criteria were identified and organized as equal sub-criteria groupings under four principal criteria: Political, Economic, Environmental and Social criteria (Table 2.4). These criteria include traditional policy management considerations such as public costs and project feasibility but also introduce new and emerging criteria for stormwater management such as the ecosystem support of a project and how it can reduce urban inequalities. For a more detailed discussion and description of the criteria, please refer to Chapter 3, section 3.2.2.

In policy making, groups who advocate and research for outcomes are influential alongside decision-makers (Mayne *et al.* 2018; Tabak *et al.* 2015).

Table 2.4: The main and sub-criteria of the analysis

Main Criteria	Political	Economic	Environmental	Social
Sub-Criteria	Existing Legislative Framework	Public Costs	Stormwater Capacity	Risk to Human Health and Safety
	Project Feasibility	Private Costs	Stormwater Quality	Civic Engagement
	Jurisdiction	Funding Availability	Ecosystem Support	Reducing Inequalities
	Implementation Time	Green Industry Growth	Energy Usage	Synergies with Other Adaptations

Considering this, three groups were identified to perform the stakeholder analysis: a green infrastructure research group (5 participants), an environmental activism group (3 participants), and a community advocate group (1 participant). With green solutions emerging as best management practice and community outreach and equity's growing importance in planning, these three groups reflect key stakeholders in urban decision making within water management. Due to Covid-19 restrictions, the analysis was performed via video. Each participant individually listed stakeholders involved in stormwater and rated their interest and influence on a scale of 0-10. The results were then aggregated within their group and a group follow up discussion reflected and adjusted the placement of stakeholders. Finally, the research group re-performed the analysis to observe any changes post-discussion which results in a tighter clustering of the stakeholders. The three groups also discussed and validated the sixteen criteria's relevance.

In total, 60 stakeholders were identified: 7 by all three groups and 14 by only two groups, in addition to some form of 'citizen'. The 60 stakeholders were classified into six types: the general public, city governance, extra-city governance, advocacy/conservancy/local structuring, research/design/construction, and other.

This research is interested in more active stakeholders and continued with the stakeholders from city governance, advocacy/conservancy/local structuring and research/design/construction. City Formal Governance includes many of the departments relevant to stormwater management. Advocacy/Conservancy are vocal contributors to policy with specific focuses on aspects of stormwater. Research/Design provides the theoretical basis for many projects and is a frequent collaborator with both other groups. These three types additionally have the most overlap between groups in the stakeholder analysis. Figure 2.3 demonstrates the distribution of the initial stakeholder placements and the distribution of the three types after discussion. While most remain high influence, they exert varying levels of interest.

The study is designed not to focus on a specific infrastructure project or specific locale within NYC. As such no indicator data was provided to the participants, i.e. monetary values regarding costs, expected times to complete projects, established environmental scoring, etc. The participants compare and score the criteria and alternatives based on their own experience and perceptions of stormwater adaptation and policy management. By focusing on the perceptions around management and not the perceptions around tangible values, it excludes any biases towards selecting what might be perceived to be the theoretical optimal choice, for example the cheapest option, the quickest to implement, or the one labeled ‘most sustainable’. It also ensures that all participants can engage with the project without needing prerequisite knowledge of a defined locale, area history, environmental conditions, or other site-specific information, information which is difficult to estimate in this top-down approach as explained in Chapter 1, Section 1.4.6. While this design may ignore characteristics of a local situation, it is intended to capture more the general trends in perception and mimics the existing urban policy documents which often discuss these adaptation strategies from an overarching, city-wide perspective.

2.4.3. Data Collection

Data was collected using an online survey where participants compared the criteria and ranked the alternatives through Zoho Survey (2021) during November-December 2020. The survey focused on the reality of NYC and not an idealized hypothetical. Initial contacts were made using the identified three stakeholder types from publicly accessible contact information and then additional contact was made through a snowball method. We collected twelve completed responses: six from governance, two from research and four from advocacy. In accordance with all rules and regulations, all participants were provided with data privacy statements and the data collection was exempt from an ethics review.

The data was analyzed using Microsoft Excel to underscore the accessibility of the method. Additionally, Excel provides a visual aspect of the data manipulation. For the AHP, GCI values were included up to the CR equivalent of 0.2. If participants

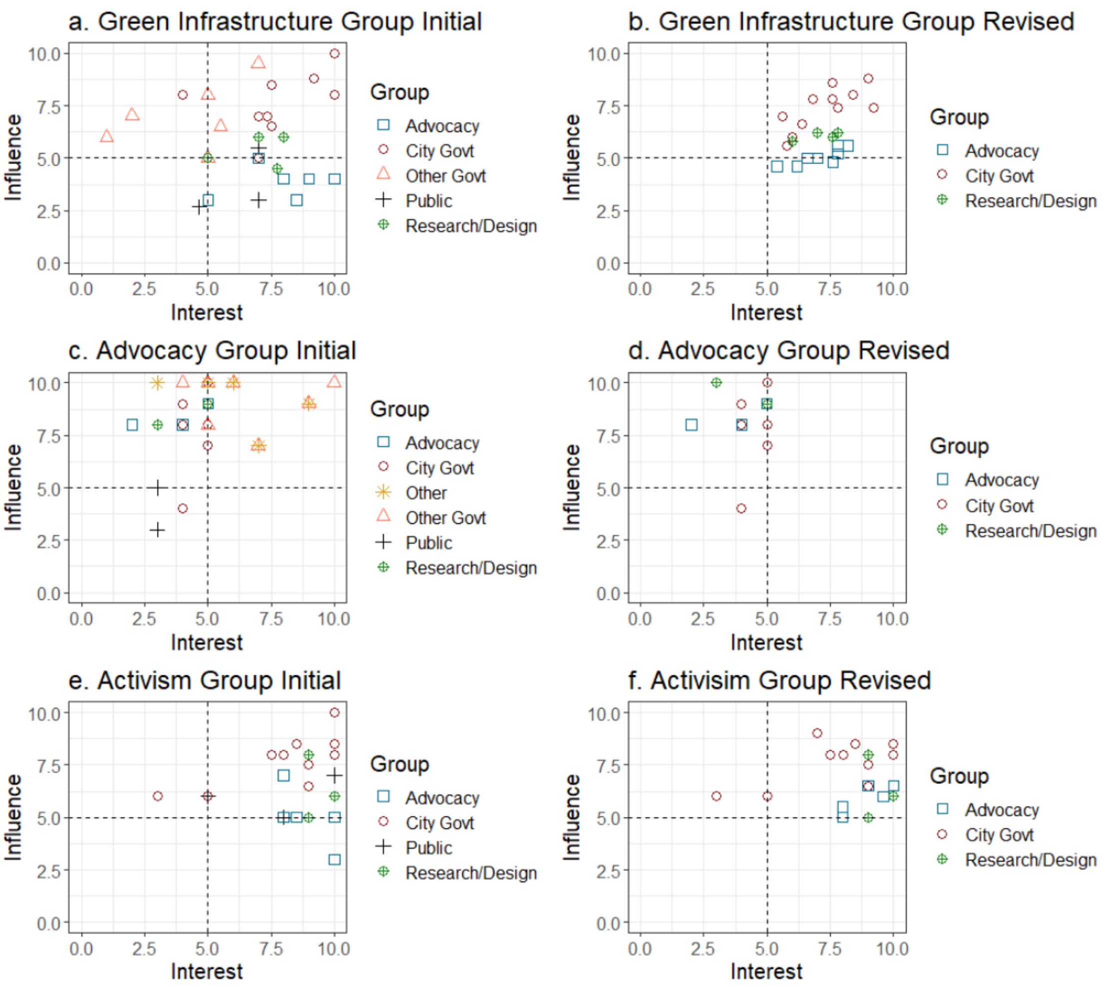

Figure 2.3: Results of a stakeholder analysis for NYC stormwater management regarding the initial placements of stakeholder categories and the final placement of stakeholder groupings from: (a,b) a green research infrastructure group, (c,d) an advocacy group, and (e.f.) an activism group.

exceeded this threshold, they were offered an opportunity to re-evaluate the inconsistent judgements or the specific matrix was excluded from analysis. Overall, 60 matrices were constructed for AHP: five per stakeholder. Only 8 matrices were excluded.

2.4.4. Results

The results underscore how the AHP-TOPSIS method is effective at identifying and quantify differences between stakeholders. This provides a basis to overcoming barriers between urban stakeholders and enact decisions acceptable to more groups. For raw data values please refer to Appendix 2.1.

2.4.4.1. Criteria Weights

The advocacy and governance groups are closer aligned with the main criteria and sub-criteria priority weights when compared to the research group (Table 2.5). Political and economic interests take priority in their weightings. Inversely, social and

Table 2.5: The AHP criteria weights for the NYC study sample with the main criteria weights and the global sub-criteria weights. Cost criteria are emphasized in bold

	Main Criteria	Full City	Advocacy	Research	Governance
	Political	0.335	0.401	0.187	0.342
	Economic	0.301	0.280	0.201	0.351
	Environmental	0.182	0.133	0.335	0.170
	Social	0.181	0.187	0.277	0.138
	Sub-Criteria (global weights)				
Political	Existing Legislative Framework	0.084	0.095	0.060	0.083
	Project Feasibility	0.102	0.165	0.035	0.088
	Jurisdiction	0.097	0.086	0.046	0.118
	Implementation Time	0.052	0.055	0.046	0.052
Economic	**Public Costs**	0.109	0.100	0.055	0.142
	Private Costs	0.054	0.054	0.028	0.064
	Funding Availability	0.104	0.088	0.088	0.115
	Green Industry Growth	0.035	0.038	0.030	0.030
Environmental	Stormwater Capacity	0.062	0.029	0.101	0.081
	Stormwater Quality	0.057	0.045	0.058	0.050
	Ecosystem Support	0.032	0.036	0.044	0.019
	Energy Usage	0.031	0.023	0.132	0.019
Social	**Risk to Human Health and Safety**	0.071	0.079	0.065	0.053
	Civic Engagement	0.029	0.033	0.049	0.019
	Reducing Inequalities	0.040	0.051	0.049	0.025
	Synergies with other Adaptations	0.042	0.024	0.113	0.040

environmental interests contribute more to the researcher's priorities. For governance, traditional methods of politics and economic concerns may explain their priorities. Advocacy, often involved in lobbying for change places a higher magnitude of importance on politics. Political will remains a large component of the effectiveness of resilience planning (Torabi *et al.* 2021). Researchers may be more insulated from these political pressures with research focuses on specialized aspects of stormwater.

While research can operate in more theoretical spaces, it still forms the basis of most environmental decisions. This disconnect between stakeholders can hamper the ability for effective adaptation planning. By identifying the importance of criteria for the city but also by group, we have demonstrated that the priorities of the city may mask those of influential stakeholders. To ensure that the decision is ultimately relevant for those involved, NYC governance can collaborate closer with researchers to ensure the exchange of knowledge and information. These differences may not ultimately disappear, but they should be understood and not a result of limited exchanges or misunderstanding.

2.4.4.2. Alternative Scores

Advocacy and research are more aligned with each other in the final performance of the five alternatives (Table 2.6). Interestingly, despite the there being an equal split between governance and non-governance participants, the ranking of the alternatives for the city overall is more aligned with the non-governance participants while governance holds more direct power in urban decision making. Despite the frequent references to green infrastructure within stormwater and flood management discourses, only governance ranks it as the top alternative. Interestingly, governance does not place government streamlining as the top priority while the other groups do. While the alternatives are theoretically separate, the ranking of the full city indicates that securing good governance is often a desired first step before construction. Of note, while government streamlining places 4th for governance the variation between 1st and 4th position is smallest for governance indicating similar levels of alternative performance.

Table 2.6: The TOPSIS scoring of the five alternatives across the NYC sample

Alternative Ranking	Full City	Advocacy	Research	Governance
1	Governmental Streamlining ***0.552***	Governmental Streamlining ***0.604***	Governmental Streamlining ***0.615***	Public Green Infrastructure ***0.557***
2	Public Green Infrastructure ***0.537***	Public Green Infrastructure ***0.523***	Maintaining Urban Environments ***0.557***	Grey Infrastructure Overhauls ***0.518***
3	Maintaining Urban Environments ***0.502***	Maintaining Urban Environments ***0.473***	Public Green Infrastructure ***0.548***	Maintaining Urban Environments ***0.5082***
4	Grey Infrastructure Overhauls ***0.477***	Private Green Infrastructure ***0.462***	Private Green Infrastructure ***0.483***	Governmental Streamlining ***0.5079***
5	Private Green Infrastructure ***0.475***	Grey Infrastructure Overhauls ***0.457***	Grey Infrastructure Overhauls ***0.421***	Private Green Infrastructure ***0.457***

Grey infrastructure is another alternative of disagreement. While disliked by advocacy and research, governance provides grey infrastructure with a higher ranking. In practice, green infrastructure is not enough to handle the capacity of rain and stormwater so grey infrastructure is needed to supplement these solutions (Moore *et al.* 2016). Therefore, the group responsible for implementing policy reflects a ranking focused on managing rainfall loads. Nonetheless, there is agreement amongst all participant groups that Private Green Infrastructure is not the best performing alternative. If governance were to implement policy based on this analysis, the other groups will not only be disappointed in the 1st position but upset at the focus on infrastructure over other softer alternatives.

The AHP-TOPSIS method again demonstrates how the differences in stakeholders can dramatically affect the policy decision. The method integrates competing voices highlighting where differences but also similarities arise. This is good for policy because local knowledge should be adapted into the decision-making framework (Cloutier *et al.* 2015). This local expertise and environmental stewardship can bring unexpected and successful management strategies within urban governance. Only by bringing together these policy perceptions can the differences truly be appreciated (Martinez-Juarez *et al.* 2019). An impressive strength of this method is its ability to demonstrate these differences in quantitative terms while still providing the option to display them in visual and compelling ways. This data interpretation fits well within the quantitative-centric policy framework and engages non-experts and the public alike thus increasing transparency of the decision-making process. While there is unlikely to ever be full consensus between stakeholders, simply engaging with the process provides deeper appreciate and acceptance of policy.

By highlighting the differences, cities can also encourage behavioral changes around environmental issues by focusing on groups' priorities and interests. By presenting environmental problems in relevant terms for a targeted audience, cities can influence urban behavior and directly engage fringe stakeholder groups who may have been excluded for the decision-making process (Garcia *et al.* 2020). This aids stakeholders who may lack the knowledge to make the decision but still exert varying levels of stewardship over the outcome. Inversely, minor stakeholders can also move governance towards their own goals by understanding how the existing system works underscoring that the social dimension of the city forms policy just as much as policy affects the social dimension (Torabi *et al.* 2021). The AHP-TOPSIS method provides exciting new ways for governance to enact more connected, localized and effective policy particularly within the complex dynamics of stormwater management.

2.4.4.3. Sensitivity Results

Due to the small sample size, the sensitivity is examined of the four principal criteria for the entire aggregated city (fig. 2.4). For all four criteria, the top-ranking alternative, government streamlining, is relatively stable, first changing with the political criterion weight is reduced around 50%. This demonstrates that the top-ranking alternative is unlikely to change with small adjustments in criteria weights. However, the sensitivity for the 4th and 5th ranked alternative is relatively high, with private green infrastructure and grey infrastructure overhauls swapping rankings with small percentage changes across all four criteria. Adjustments in the criteria weighting could influence a ranked policy strategy. The visualization of the sensitivity allows us to observe the relationship between the alternatives and criteria. Here, grey infrastructure is positively influenced by political bias but negatively by social bias. Policy makers can reflect on how their decisions would have changed as the needs of the city vary through time allowing for deeper connections between present and future policies.

2.4.5. Limitations

While the sample study demonstrates the effectiveness of the AHP-TOPSIS methodology, there are still certain limitations. The example has not considered quantitative values attributed to the alternatives but rather relies on previous experience and perceptions. As not all stakeholders have extensive direct engagement with the stormwater decision making process, some perceptions might be misrepresenting the reality of the alternatives. As the study has not focused on a specific site, we have only demonstrated the perceptions towards a preferred management instead of an actual preferred management. However, understanding what stakeholders perceive is useful in designing future site specific studies to acknowledge that some management techniques should be excluded or emphasized.

The study has also not accounted for the geographic diversity within the city. Where the stakeholders are located within the city and their previous experiences shape their responses. While this can provide us with generalized trends in NYC urban

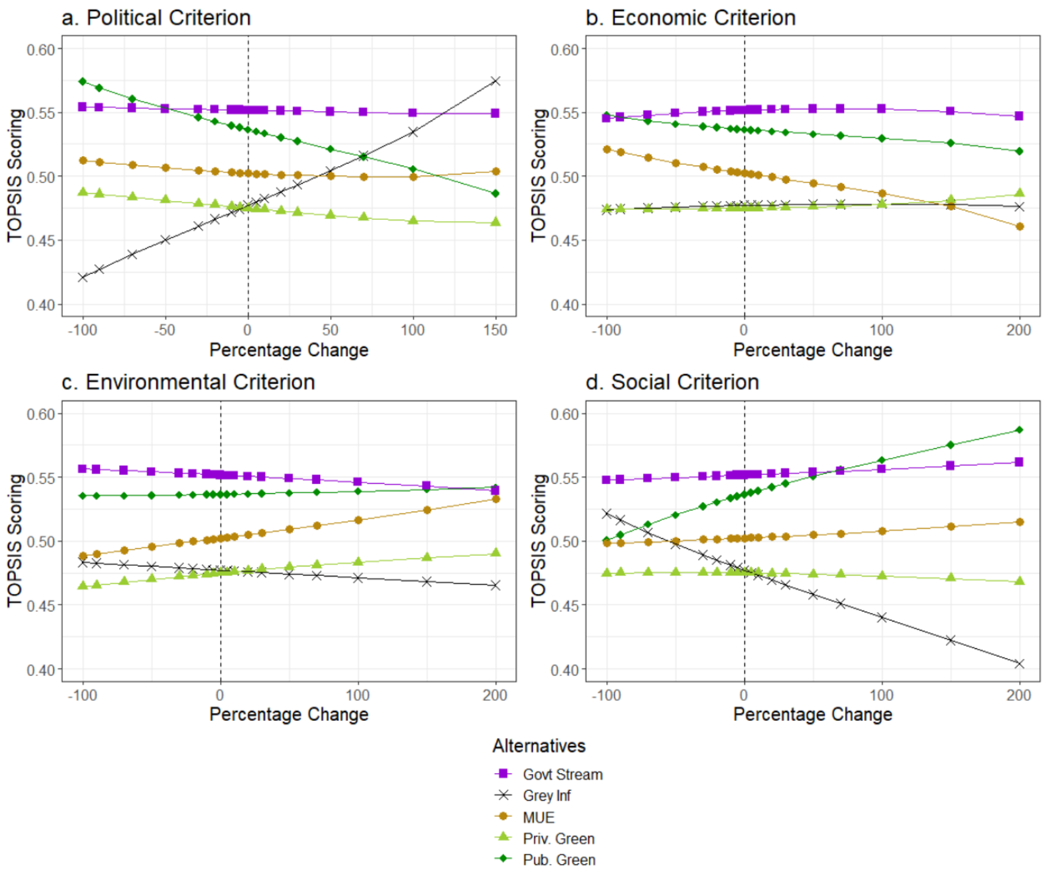

Figure 2.4: The sensitivity analysis results of shifting the weight of a criterion and the resulting TOPSIS ranking of the alternatives for the a. political, b. economic, c. environmental and d. social criterion with government streamlining (govt), grey infrastructure overhauls (grey inf), maintaining urban environments (MUE), private green infrastructure (priv. green), and public green infrastructure (pub. green).

management it does not distinguish between the more and less flood susceptible neighborhood of the city.

While the study has presented the AHP-TOPSIS methodology as a user-friendly tool for policy decisions, there will always be some stakeholders who either choose not to engage with the methodology or are unable to process the methodology. While the concepts have been presented in a more general way, some of these can still pose a barrier to non-experts with the mathematical and computational prerequisites. It is recommended that an expert is always included in the use of the methodology. However, without oversimplifying the method, the way the study has presented the AHP-TOPSIS methodology has reduced the burden of complexity to engage non-expert and non-technical decision makers with MCDA tools for decision making.

2.5. Chapter Conclusions

The AHP-TOPSIS method is an effective aid for urban climate adaptation decision-makers. Building upon various aspects of the existing methodology this chapter has combined a methodology that is effective at demonstrating differences between stakeholders. The results of the methodology, alongside the suggested sensitivity analysis, allow for simple yet engaging results encouraging the integration of the method within the existing policy framework. The chapter successfully presents an AHP-TOPSIS methodology that connects to the theoretical discussions of MCDA, allowing for decision-makers to understand the mechanics of the method, while still being accessible for a non-expert audience. Particularly for climate change, the method can incorporate uncertainty from many forms. Variations in climate projections, qualitative attributes and uncertainty in personal judgements are all easily absorbed by this method. The approachability of the method for experts and non-experts alike encourages deeper stakeholder engagement with the decision-making process. A tool can only be effective if the users understand the nature of the tool.

The greatest strength of the method is to account for different stakeholder opinions while being easily adapted to local contexts. The method is responsive to the differences and similarities of different stakeholders and allows policy makers to examine where these differences emerge, how local knowledge effects the results and to display these results in equal, quantitative terms. While stakeholder differences are well observed, the quantification of these differences connects the methodology with the existing focus on numerical decisions all while avoiding a reliance on monetary terms and incorporating emotional and qualitative judgements.

In the worked NYC sample study, the chapter demonstrates that not every participant prefers green infrastructure for stormwater flood management, despite the alternative’s emergence as a priority in stormwater discourses. There is also disagreement over the importance of criteria between stakeholders in the city. This opens the possibility to further explore why these differences have emerged and how this will affect future stormwater policy within the city.

This method is contextually and geographically flexible, only requiring a shift in the framework of the decision. While presented for stormwater here, the method is adaptable for other urban adaptation problems cities face. It presents an exciting opportunity to continue to adapt additional MCDA methods for policy makers and incorporate decisions that rely on overarching climate change urban issues. In the following chapter, the method is applied to a more global focus of stormwater management to identify if any patterns of adaptations can be used to construct adaptation guidelines for urban stormwater management.

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Appendix 2.1 Raw data values

Table A2.1.1: Group aggregated by consistency non-normalized AHP weights for the main criteria

	Participant Grouping			
Main criteria (weighted non normalized)	Full City	Advocacy	Research	Governance
Political	1.39517	1.74520	0.77042	1.48504
Economic	1.25384	1.21807	0.82609	1.52637
Environmental	0.75700	0.57777	1.37913	0.73690
Social	0.75515	0.81419	1.13929	0.59868

Table A2.1.2: Group aggregated by consistency non-normalized AHP weights for the sub-criteria

		Participant Grouping			
Main Criteria	Sub-Criteria (weighted non-normalized)	Full City	Advocacy	Research	Governance
Political	Existing Legislative Framework	1.03691	1.02039	1.31607	1.01144
	Project Feasibility	1.25046	1.78371	0.75984	1.07790
	Jurisdiction	1.20061	0.93341	1.00000	1.44267
	Implementation Time	0.64237	0.58862	1.00000	0.63580
Economic	Public Costs	1.59750	1.53691	1.22738	1.89734
	Private Costs	0.78939	0.83086	0.61907	0.84872
	Funding Availability	1.53171	1.35002	1.96799	1.52884
	Green Industrial Growth	0.51772	0.58007	0.66874	0.40619
Environmental	Stormwater Capacity	1.42394	0.89177	1.31607	2.33831
	Stormwater Quality	1.31854	1.38367	0.75984	1.44962
	Ecosystem Support	0.74934	1.12138	0.57735	0.53252
	Energy Usage	0.71078	0.72270	1.73205	0.55399
Social	Risk to Human Health and Safety	1.65645	1.86297	1.00000	1.66527
	Civic Engagement	0.67651	0.77108	0.75984	0.60740
	Reducing Inequalities	0.92178	1.21030	0.75984	0.79229
	Synergies with other Adaptations	0.96809	0.57518	1.73205	1.24784

Table A2.1.3: Group aggregated TOPSIS distance from ideal positive (S^{+}) and negative (S^{-}) solution and closeness coefficient (C^{*}) of the policy alternatives

			Policy Alternatives				
			Grey Inf. Overhauls	Public Green Inf.	Private Green Inf.	Govt Streamlining	Maintaining Urban Env.
Participant Groupings	Full City	S^{+}	0.229541	0.192058	0.221331	0.185186	0.198358
		S^{-}	0.209432	0.22235	0.200268	0.227841	0.200187
		C^{*}	0.477095	0.536549	0.475021	0.551638	0.502294
	Advocacy	S^{+}	0.228438	0.193255	0.216431	0.15417	0.204778
		S^{-}	0.192108	0.211999	0.185934	0.235225	0.183549
		C^{*}	0.456806	0.523127	0.462103	0.604078	0.472666
	Research	S^{+}	0.250971	0.180187	0.204769	0.146126	0.180968
		S^{-}	0.182315	0.218415	0.191445	0.233557	0.227955
		C^{*}	0.420772	0.547953	0.483186	0.615137	0.557453
	Governance	S^{+}	0.226206	0.19486	0.248009	0.222291	0.20385
		S^{-}	0.24322	0.24474	0.208783	0.229404	0.210696
		C^{*}	0.518122	0.556733	0.457063	0.507873	0.508258

Chapter 3: Global perceptions and priorities in urban stormwater adaptation management towards adaptation alternatives*

*Adapted from Axelsson, C., Giove, S., Soriani, S. and Culligan, P. (2021) 'Urban pluvial flood management Part 2: Global perceptions and priorities in urban stormwater adaptation management and policy alternatives', *Water*, 13, 17, 2433, https://doi.org/10.3390/w13172433.

3.1. Introduction

Changing rainfall patterns are forcing cities to embrace climate adaptation strategies. As explored in both Chapters 1 and 2, high intensity rainfall or cloudburst events are expected to increase in urban areas due to climate change with the potential to overwhelm city infrastructure causing localized flooding and potential environmental, financial and social damages (Axelsson *et al.* 2021; 2020; Rosenzweig *et al.* 2019). Regardless of whether a city is retrofitting legacy existing infrastructure or implementing new systems to manage 21st century growth, the need to create rainfall adaptation projects that can be implemented under current stresses while planning for future variability is almost universal.

Adaptation initiatives are difficult to conceptualize alongside uncertainty within climate change projections. While climate change mitigation can provide a framework around numeric reduction targets and foster a global 'do-your-part' community, climate change adaptation has less defined boundaries. Fundamentally, adaptation needs to be flexible. Overtime, and highly dependent on climate mitigation efforts and our refinement of climate models, rainfall patterns and projections can change (Collins *et al.* 2013). In addition, the intensity of rainfall changes is not just dependent on the home country's mitigation efforts, but the global community's efforts. It is time and resource intensive to plan for a range of futures while acting on shifting and immediate threats. It is also important to realize while preparing for potentially adverse climates, that adaptation should not be synonymous with disaster management (Dilsak and Prakash 2018). Adaptation is not a means to protect and uphold our current existence from climate change, but rather provide us the tools to reorganize our existence to new climate realities. The multifaceted dynamics of adaptation hinders the development of uniform adaptation initiatives.

At the urban level, adaptation is positioned to solve multiple problems simultaneously. Within stormwater management, Chapter 1 establishes green infrastructure as emerging as best management practice for handling rainfall. Green and blue-green infrastructure mimics natural patterns of rainfall management by absorbing, filtering or delay-releasing rainfall volumes to the urban environment, oftentimes but not necessarily with a visual natural component, as compared to traditional grey concrete infrastructure focused on the removal of rainfall volumes. These infrastructure systems for stormwater management compliment the future vision of eco and technological cities (Joss *et al.* 2013); They can provide aesthetic value, increase property value and provide ecological services, all while combating urban inequality to green space access. Coincidentally, investors are more easily persuaded towards green infrastructure for the immediate returns from these values over the long-term flooding benefits reaped by future generations (Antrobus 2011). Yet, green infrastructure for rainfall management is normally regulated for water and runoff management alone, with the other advantages considered only as co-benefits (McPhillips *et al.* 2020). Thus, although green infrastructure is primarily considered an adaptation strategy for managing increased urban rainfall volumes it cannot be discussed without considering the multi-criteria nature of its design. Additionally, green infrastructure has not replaced other traditional and emerging management practices and must be considered amongst the other adaptation techniques available.

There are no global uniform standards for climate adaptation, but cities are positioned as centers of influence in this discussion. With most of the world living in urban areas, paired with the emerging economic dominance of cities within their respective countries, cities become representatives in coordinating climate action on a global scale. In joining and networking within organizations such as C40 or CDP, cities engage in a global community to tackle urban climate issues while sharing local knowledge and strategies, which is moving urban adaptation closer to a coordinated international effort (C40 2021; C40 2021). With this international backing, these cities can influence their own regional and national governments setting standards for smaller municipalities to follow. Cities, therefore, have the influence to direct the global conversation of climate adaptation.

Increasing rainfall intensity is an urban issue, but who is influential in the adaptation decision-making process is less defined. There are different levels of knowledge and engagement between the average urban citizen and the informed policy maker. Additionally, differing interest groups have stakes in the ecological, economic or social interests of rainfall management strategies. Between those who make, enforce, advocate for or research adaptation strategies, there are multiple angles to evaluate stormwater adaptation. Furthermore, the impacts of pluvial flooding are dependent on urban geography and marginalized, minority or impoverished groups may be disproportionately located in geographically vulnerable neighborhoods (Fahy *et al.* 2019; Colten 2006). Adaptation policy must account for the opinions of those directly affected and consider equity in their approaches. The addition of stakeholder voices can be beneficial for green infrastructure and stormwater management where existing strategies might be too narrow in their focus (Liu *et al.* 2019). While incorporating more groups into policy making allows for deeper social learning and can benefit policy by embracing experience and local knowledge, it can also obscure minority opinions or promote misguided strategies (Von Schonfeld *et al*. 2020). Therefore, it is difficult to quantify what the opinions on policy are within an urban area amongst the competing voices. Without understanding where stakeholders envision policy moving towards, it is difficult to organize standards for adaptation.

Regardless of the complexities around urban stormwater adaptation, cities increasingly need to enact policy to combat rainfall extremes. This chapter aims to establish the international trends in the preferences for climate-rainfall adaptation using the six dynamic and international developed cities across North America, Europe and Australasia; New York City (NYC), Vancouver, Copenhagen, Amsterdam, Sydney and Auckland. By understanding the balance between policy uniformity and local characteristics, the chapter presents guidance for cities undertaking adaptation policy.

3.2. Research Methodology

To understand the variations in stakeholder opinions on stormwater adaptation, the chapter employs the combined multi-criteria decision analysis (MCDA) methodology of the Analytic Hierarchy Process (AHP) (Saaty 1980) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon 1981), introduced in Chapter 2 (Axelsson *et al.* 2021). Therefore, the proposed MCDA is made of four components: who is making the decision, what criteria influence the decision, how do the alternatives perform under these criteria and how sensitive are the results to variations. After first establishing the main parameters of the MCDA, the AHP, through pairwise comparisons, is used to determine the weight of each criterion in the process. Incorporating these weights, TOPSIS is used to determine the performance of each alternative so that they can be ranked, and a best performing solution can be selected. For the technical functions of the MCDA, please refer to Chapter 2.

3.2.1. Cities and the Stakeholders

To understand the global perceptions towards stormwater adaptation, this chapter integrates the six cities previously examined in Chapter 1: NYC, Vancouver, Copenhagen, Amsterdam, Sydney (City of Sydney) and Auckland. As established, the six cities are global centers with strong economies, connections and research capacities providing them access to global adaptation discussions as representatives of their regions and nations. This representation also affords them to be held as case or comparison studies for other municipalities within their own region or on the global stage. Additionally, these six cities are demonstratively actively pursuing adaptation policy to retrofit their post-industrial infrastructure systems and they represent varying levels of centralized governance within the three regions of North America, Europe and Australasia.

In Chapter 2, three stakeholder groups are determined to be relevant for stormwater management within NYC: formal city governance, research and advocacy/conservancy. Here, all three groups are extended to the six cities as these categories represent three types of stakeholders in urban policy: those who make policy, those whose work supports policy and those who lobby policy. In every municipality, the basic function of governance and policy making is crucial despite various levels of public expenditure on civil projects. Formal policies on stormwater management require governance and in order to form such regulation, governance relies on informed research. This research can be undertaken internally or externally but in cities with large research universities there exists legacy partnerships between the governance and research systems. Furthermore, in a democratic city, advocates for policy can actively leverage their concerns through protests and the electoral process thus guiding governance towards specific concerns. While each of these case-study cities may have additional and unique important stakeholder groups, these three groupings are universal across the cities and allow for comparisons between them. While other stakeholder groups such as ‘citizens’ can be considered universal, here the chapter is focused on stakeholders with experience in policy formation or the science of stormwater to make informed perceptive decisions on future management and adaptation. Thus, these three stakeholder groups are incorporated into the analysis.

3.2.2. The criteria

Here sixteen criteria, organized into four main criteria, are selected as important to the urban rainfall adaptation decision-making process, as determined in Chapter 2 (Table 3.1). While selected from the six cities and applied to NYC, this chapter argues the universal justification of the criteria for the six cities as it is important that the criteria are relevant to the decision makers **(**Pakfetrat *et al.* 2020). Additionally, a large scope of criteria is included to prevent the disenfranchisement of individuals important to the adaptation process (Baron and Petersen 2015).

Table 3.1: Organization of the criteria and their description

Main Criteria	Description
Political (Pol)	This criterion is concerned with political ability, actions and concerns regarding policy management. It includes the legislative and political framework for making decisions as well as the ability to execute policy.
Economic (Econ)	This criterion is centered around the financial considerations and concerns regarding policy management. This captures the costs and savings of both public and private financing as well as industrial engagement.
Environmental (Env)	This criterion focuses on the environmental responses and needs in policy management. It includes the ecological components of water and environmental management in the city as well as the connections to climate change.
Social (Soc)	This criterion captures the social and urban functionality in policy management. It includes the actions of citizens and policies' effects in daily life while also considering the social benefits of urban management.

Main Criteria	Sub-Criterion	Description
Political	Existing Legislative Framework (ExLF)	The existing laws, regulations and directives in the city that set the basis and allow for the further development of stormwater management policies
	Project Feasibility (ProjF)	The political will, planning framework and technical skills available to the city to implement new policy and management alternatives
	Jurisdiction (Juris)	The city's ability to directly implement and manage policy relating to stormwater through control and input over the responsible agencies or departments
	Implementation Time (ImpTime)	The timeframe for a policy or management alternative from proposal through implementation
Economic	Public Costs (PubCost)	The construction and maintenance costs of an alternative that the city or public body pays for
	Private Costs (PriCost)	The construction and maintenance costs of an alternative that private entities or individuals pay for
	Funding Availability (FundAv)	The availability of funding from internal, local, regional, national or international bodies to help with costs

	Green Industry Growth (GIG)	The ability for the environmental business and governmental sectors that focus on green technologies, services and products to develop and grow while focusing on a policy alternative
Environmental	Stormwater Capacity (StormCap)	The ability of an alternative to manage stormwater volumes
	Stormwater Quality (StormQua)	The ability of an alternative to manage the water quality of stormwater by managing and removing pollutants
	Ecosystem Support (EcoS)	The capacity of an alternative to support healthy, local, biodiverse ecosystems in the city
	Energy Usage (EnU)	The energy consumption required by an alternative from construction through management
Social	Risk to Human Health and Safety (RiskHHS)	The potential for the alternative to pose dangers to the public directly or indirectly during the life cycle of the alternative such as construction dangers, road use dangers, contaminated water, etc.
	Civic Engagement (CivEng)	The ability and willingness for citizens to engage in policy management and take initiative in adaptation strategies from the proposal stage through the implementation of the alternative
	Reducing Inequalities (RedIneq)	The extent the policy provides opportunities to reduce urban inequalities, example: economic, access to healthcare, access to environment, etc. and provides the potential for local employment
	Synergies with other Adaptations (SynAd)	The extent the policy contributes to overall urban health and protecting against other hazards to urban populations, example: pollution, air temperature, drought, etc.

Policy is a product of politics. With new climate adaptations, the ‘Existing Legislative Framework’ sets the foundation for the evolution of future projects. Within this evolution, political will is a driver of policy. However, for climate change, political systems need not only to be willing to implement policy changes but must themselves become resilient to climatic pressures as they strain the urban social network (Torabi *et al.* 2021). ‘Political Feasibility’ captures both this will to make policy change, but also the possibility to implement and manage change. This pairs with ‘Jurisdiction’ to cover the political limitations to policy management. Cities might be better positioned to transition towards adaptation and resiliency projects if there exists the political infrastructure to support environmental decisions (Holden and Larsen 2015). Finally, ‘Implementation Time’ captures the urgency of adaptation but also the dynamics of short term versus long term political strategies. Ultimately, adaptation is always subject to political interpretations and needs (Sovacool *et al.* 2015). However, politics alone does not capture the full extent of criteria.

Economically, rainfall adaptation presents both costs and future opportunities for cities. Firstly, the 'Public Costs' of adaptation born by the city and the 'Private Costs' of adaptation to individuals need to be evaluated. In addition to these costs, cities must evaluate the 'Funding Availability' for adaptation projects across various levels of governance and public-private partnerships. How a city finances green infrastructure can help determine how effective the project will be considering which design elements and co-benefits are prioritized (Tubridy 2020). The investments in adaptation projects can also simultaneously spur 'Green Industry Growth'. With new technologies emerging, cities can take advantage and grow their industrial sectors while contributing to the green economy thus securing their competitive position in the global market (Georgeson and Maslin 2019).

Environmental criteria play a role in the discussion around rainfall management. 'Stormwater Capacity' is an initial criterion in rainfall management as it handles the total load of water. However, as traditional infrastructure and combined sewage systems can leak pollution to the environmental, 'Stormwater Quality' emerges as an important consideration. 'Ecosystem Support' captures many of the ecological co-benefits and ecosystem services that are often difficult to quantify but still important in the decision-making process. Finally, with a continued focus on urban climate change mitigation, 'Energy Usage' directly ties the adaptation project back to emissions.

Socially, cities are framing adaptation projects to solve multiple urban issues. As with all urban projects involving infrastructure, cities are concerned with the 'Risk to Human Health and Safety' of a project. Yet, adaptation projects are not always understood, followed or cared for by the local population so the level of 'Civic Engagement' is important to ensure projects become integrated into daily life. Additionally, adaptation projects are not always uniformly implemented across the city and as green infrastructure for stormwater management presents many co-benefits, rainfall adaptation becomes susceptible to urban inequalities. Wealthier areas receive higher levels of initial green infrastructure investments (Sanchez and Reames 2019; Heckert and Rosan 2016; Shi *et al.* 2016). Green infrastructure is thus linked to environmental justice (Wolch *et al.* 2014) and is captured by 'Reducing Inequalities'. Finally, 'Synergies with Other Adaptations' connects the multi-criteria nature of stormwater adaptation projects to the climate as a system rather than disconnected issues.

All sixteen of the sub-criteria shown in Table 3.1, as well as the four main criteria groupings that capture the range of priorities in urban climate rainfall adaptation. While each city may have additional concerns, these criteria represent universal concerns across the six cities and influence their policy making decisions.

3.2.3. The alternatives

Continuing with the results of Chapter 1 and the applied method of Chapter 2, this chapter incorporates the five established policy alternatives for urban stormwater adaptation: Grey Infrastructure Overhauls, Public Green Infrastructure, Private Green Infrastructure, Government Streamlining and Maintaining Urban Environments. While in practice these five alternatives are often used in tandem, here they are discussed as theoretically different policy options for implementation. Thus, the study can observe how each alternative, dependent on their own strengths and weaknesses, performs under the criteria weights to help determine if there is a universal hierarchy in preference towards the alternatives.

While several classifications of heavy precipitation exist, there is no uniform definition and here, the chapter does not define a threshold for heavy rainfall (Collins *et al.* 2013). Rather, each of the six cities has existing thresholds and design guidelines for rainfall volumes in their respective regulations to which the existing and historical infrastructure has been built. These five alternatives are thus being discussed within each city as a response to exceeding city-based thresholds, regardless of the actual rainfall total. While acknowledging that certain alternatives and strategies might not be sufficient if the magnitude of extreme precipitation exceeds expectations, these five policy alternatives still represent the strategies that all six cities wish to utilize for their expected increases in heavy rainfall events.

3.2.4. Data collections

The data was collected over a three-month period from December 2020 to February 2021. Initial contacts were selected from the three stakeholder categories in the six cities. Following these initial contacts, additional participants were selected using a snowball method through their social and professional networks (Goodman 1961). Participants were provided a description of the problem, criteria and alternatives and then asked to perform a survey where through linguistic judgements they would judge the criteria and the alternatives using Zoho Survey (Zoho 2021). Please see

Table 3.2: The spread of the 34 participants

Region	$n = 34$	Governance	Advocacy	Research
North America	New York City	6	4	2
	Vancouver	5		4
Europe	Copenhagen		2	
	Amsterdam	3	1	
Australasia	Sydney		2	2
	Auckland	1	1	1

Appendix 3.1 for the survey user guide. Similar to the example explored in Chapter 2, the participants approached this survey from a theoretical perspective, relying on their own experiences and judgements towards stormwater management in their respective city. Participants were provided the opportunity to re-evaluate their judgements if inconsistencies were discovered during the analysis phase. A total of 34 participants out of 50 provided completed responses and are included in the analysis (Table 3.2). The full analysis was performed in seven groupings: the full participants, by stakeholder group (governance, advocacy and research) and by region (North America, Europe and Australasia).

3.3. Results and Discussion

The results present a unique and quantitative picture of the preferences towards future urban rainfall adaptation across the six cities. In the preferences of the criteria and alternatives, key differences emerge between the groups while, on the other hand, some level of consensus is achieved. Here these differences are discussed as well as the consensuses, and the implications this has on establishing an international framework for pluvial flood adaptation. Please refer to Appendix 3.2 for raw data values.

3.3.1. Criteria weights

The criteria weightings reveal that the priorities for rainfall adaptation share similarities between the stakeholders but lack uniformity. Of the 170 matrices produced for the AHP, only 30 matrices were excluded for containing an undesirable level of uncertainty. When examining the four main criteria across the seven analyses, the political criterion has the highest average weight of 32% while the social criterion carries the lowest average weight at 19%. (Table 3.3). Additionally, across the three regional analyses, the political and economic criteria exhibit higher priorities than the environmental and social criteria which is reflected in the entire participant analysis.

Table 3.3: The criteria weights of the four main criteria and the global weights of the sixteen sub-criteria across the seven analyses with abbreviations as defined in Table 3.1

		Aggregated by Stakeholder			Aggregated by Region		
	Total Participants	Governance	Advocacy	Research	North America	Europe	Australasia
Main Criteria	Pol (0.320)	Econ (0.335)	Pol (0.371)	Pol (0.280)	Pol (0.323)	Econ (0.355)	Pol (0.310)
	Econ (0.276)	Pol (0.323)	Soc (0.252)	Env (0.276)	Econ (0.266)	Pol (0.313)	Econ (0.248)
	Env (0.219)	Env (0.204)	Econ (0.224)	Econ (0.243)	Env (0.217)	Env (0.205)	Env (0.234)
	Soc (0.185)	Soc (0.138)	Env (0.153)	Soc (0.201)	Soc (0.194)	Soc (0.128)	Soc (0.208)
Global weights of the sub-criteria	PubCost (0.110)	PubCost (0.145)	ProjF (0.159)	ProjF (0.109)	PubCost (0.110)	PubCost (0.129)	ProjF (0.147)
	ProjF (0.107)	Juris (0.102)	RiskHHS (0.127)	Storm Cap (0.104)	ProjF (0.096)	PriCost (0.105)	RiskHHS (0.120)
	FundAv (0.082)	FundAv (0.088)	ExLF (0.085)	PubCost (0.096)	Juris (0.090)	Storm Cap (0.104)	StormCap (0.111)
	RiskHHS (0.082)	ProjF (0.086)	PubCost (0.081)	RiskHHS (0.087)	ExLF (0.088)	ProjF (0.103)	PubCost (0.093)
	ExLF (0.081)	ExLF (0.082)	Juris (0.080)	EcoS (0.073)	RiskHHS (0.082)	FundAv (0.091)	FundAv (0.086)
	Juris (0.081)	StormCap (0.082)	FundAv (0.080)	ExLF (0.072)	FundAv (0.076)	Imp Time (0.081)	ExLF (0.075)
	StormCap (0.079)	PriCost (0.073)	Storm Qual (0.050)	FundAv (0.070)	Storm Qual (0.067)	Juris (0.065)	Juris (0.064)
	StormQual (0.058)	RiskHHS (0.056)	RedIneq (0.047)	Storm Qual (0.061)	Storm Cap (0.062)	ExLF (0.063)	Storm Qual (0.052)
	PriCost (0.055)	StormQual (0.055)	ImpTime (0.046)	Juris (0.050)	EcoS (0.051)	EcoS (0.048)	PriCost (0.052)
	EcoS (0.051)	ImpTime (0.052)	CivEng (0.046)	Imp Time (0.049)	Imp Time (0.050)	SynAd (0.043)	EcoS (0.045)
	ImpTime (0.051)	EcoS (0.041)	PriCost (0.040)	SynAd (0.048)	PriCost (0.046)	RiskHHS (0.037)	SynAd (0.033)
	SynAd (0.039)	SynAd (0.034)	Storm Cap (0.040)	PriCost (0.047)	SynAd (0.040)	Storm Qual (0.034)	CivEng. (0.032)
	CivEng (0.034)	GIG (0.028)	EcoS (0.038)	CivEng (0.040)	RedIneq (0.038)	CivEng (0.031)	EnU (0.026)
	RedIneq (0.031)	EnU (0.026)	SynAd (0.031)	EnU (0.038)	EnU (0.037)	GIG (0.029)	ImpTime (0.024)
	EnU (0.031)	RedIneq (0.025)	EnU (0.026)	GIG (0.031)	CivEng (0.035)	EnU (0.019)	RedIneq (0.023)

GIG (0.029)	CivEng (0.023)	GIG (0.023)	RedIneq (0.027)	GIG (0.033)	RedIneq (0.017)	GIG (0.018)

Despite the differences in regional histories and characteristics as well as the bias in the data set towards participants from North America, the six cities converge on this similar criteria weight structuring. However, when the participants are separated by stakeholder type, differences arise between the criteria weights. These differences infer that the participant's stakeholder typology is more influential in determining their criteria preferences than where the participant is located but that when the stakeholders within a city are aggregated together, these individual preferences merge into similar global trends, either similarly obscuring or smoothing the differences within the six cities.

The global criteria weightings of the sub-criteria, considering their parent criterion weight, exhibit similar trends to the main criteria. On average, 73% of the top half of the weighted sub-criteria across the seven analyses were either political or economic criteria. Nonetheless, the four highest average weighted sub-criteria were Project Feasibility (Political), Public Costs (Economic), Risk to Human Health and Safety (Social) and Stormwater Capacity (Environmental). While the focus of criteria weights overall is on the political and economic, certain aspects of social and environmental concerns outweigh the others. However, the capacity of infrastructure and the potential risk to human health and safety are traditional concerns in stormwater management and also urban infrastructure considerations and they do not directly reflect the emerging focus on green solutions and their multi-dimensional benefits within urban climate adaptation policy.

The global weights of environmental and social sub-criteria are lower across the analyses. Particularly, Civic Engagement (Social), Reducing Urban Inequalities (Social), Energy Consumption (Environmental) and Green Industrial Growth (Economic) on average rank as the lowest criteria for urban rainfall adaptation. However, these four criteria capture a large part of the emerging focus of climate change policy. Landmark climate legislation proposals such as the American Green New Deal (H. Res 109) explicitly discuss the importance of these criteria. Therefore, here we observe a disconnect between how climate change policy is theoretically discussed versus the perceptions of stakeholders involved in drafting and managing this policy in reality. This presents a barrier in implementing policy. For immediate threats, this disconnect can cause delays in action while for long term strategies, policy structured for past priorities might be unsuccessful in answering future demands. The research does not advocate for which type of criteria should be presented as the most important, but rather highlights the gap between theory and reality and that more work needs to be done to ensure that policy is responding to our criteria needs.

The observed criteria weights across the seven analyses are highly dependent on the criteria inputs themselves and the weights may be subject to change. The addition of new criteria information could alter how the weightings unfold. While we capture some co-benefits of green technologies, we did not capture all co-benefits such as aesthetics and recreation as they go beyond the explicit scope of stormwater management (Derkzen *et al.* 2017). How the decision maker structures which criteria are included in the analysis can influence the weightings. However, because we initially organized the criteria into four main criteria groupings and these weights were also tested, we discover that overall, political and economic concerns continue to dominate the criteria weightings when compared to social and environmental considerations.

3.3.2. Alternative rankings

The performance of the five policy alternatives demonstrates mixed agreement between the stakeholders over the alternative preferences. For each analysis, public green infrastructure emerges as the most satisfactory alternative and in six of the seven analyses, government streamlining is ranked second while grey infrastructure overhauls is the least satisfactory (Table 3.4). However, the range between these top and bottom performing alternatives is small; a TOPSIS score difference of around 0.13 on average. Additionally, the average score of every alternative was 0.51 or 51% satisfaction with no alternative breaking 60%. No alternative presents itself significantly more satisfactory over the others and the alternatives' scores are clustered together. Nonetheless, the trends in the overall ranking of the alternatives does reveal that preferences exist within the participants.

Unlike the criteria weightings, there is more agreement between the stakeholder groupings in the ranking of the alternatives. The only difference being within the governance group where the 3rd and 4th alternative position shift compared to advocacy and research. Despite the disagreements over what criteria are important in evaluating the urban rainfall adaptation process, governance, advocacy and research

Table 3.4: The TOPSIS scores of the five policy alternative: public green infrastructure (pub green), private green infrastructure (priv green), grey infrastructure overhauls (grey inf), maintaining urban environments (MUE) and government streamlining (govt stream)

		Aggregated by Stakeholder			Aggregated by Region		
Alternative Ranking	Total Participants	Governance	Advocacy	Research	North America	Europe	Australasia
1	**Pub Green** (0.566)	**Pub Green** (0.568)	**Pub Green** (0.565)	**Pub Green** (0.575)	**Pub Green** (0.556)	**Pub Green** (0.542)	**Pub Green** (0.597)
2	Govt Stream (0.534)	Govt Stream (0.537)	Govt Stream (0.561)	Govt Stream (0.526)	Govt Stream (0.543)	Govt Stream (0.537)	Priv Green (0.553)
3	Priv Green (0.506)	MUE (0.512)	Priv Green (0.505)	Priv Green (0.518)	MUE (0.506)	Priv Green (0.499)	MUE (0.504)
4	MUE (0.500)	Priv Green (0.492)	MUE (0.492)	MUE (0.500)	Priv Green (0.493)	Grey Inf (0.469)	Govt Stream (0.500)
5	Grey Inf (0.445)	Grey Inf (0.469)	Grey Inf (0.392)	Grey Inf (0.449)	Grey Inf (0.471)	MUE (0.461)	Grey Inf (0.366)

reach similar conclusions about which alternative best answers these needs. Therefore, while there is disagreement over the decision-making process between the groups, the outcome is likely to satisfy their competing interests. This is encouraging for rainfall management as these disagreements might not prevent dissatisfaction with policy itself, allowing for immediate decisions to be made while discussions continue about how to formulate future policy.

When organized by region, stronger differences arise between the stakeholders. Despite having similar criteria weightings, the three regions exhibit different alternative ranking. Considering the larger volume of responses from North America, public green infrastructure nonetheless continues as the highest ranked alternative across the three regions. Policy makers and governments tend to prefer highly visible infrastructure projects as they convey action and are demonstratable projects during election cycles (Dilsak and Prakash 2018). Paired with the focus on a greener city, stakeholders may be conditioned to this alternative designating it a favorable TOPSIS score. However, grey infrastructure is also a large and visible infrastructure intervention that can be better at handling pure stormwater capacity (Alves *et al.* 2020; 2019). Green infrastructure alone might not be able to manage an entire city's stormwater strategy (Li *et al.* 2021; Zhang *et al.* 2021). Additionally, cities have the existing skill set and budgetary framework to quickly implement grey infrastructure, yet the regions do not universally prefer it. Green infrastructure continues to emerge as a best management practice for stormwater and the regions prefer this alternative. While the criteria weights do not reflect the current discourses on climate change legislation, the alternative rankings capture these emerging preferences.

Considering green infrastructure, the satisfaction level of private green infrastructure varies across North America, Europe and Australasia. More decentralized governance systems are better optimized to handle private and individual investments and here we observe that North America, with the least decentralization, shows less preference for these investments (Engberg 2018). The variation in private green infrastructure also disconnects from the theory of stormwater management, especially strategies with a focus on public green infrastructure, as the private investments help close the gaps within the urban green system (Rosenzweig *et al.* 2019). However, private green investments are more difficult to regulate than public strategies and come with additional barriers to implementation within the general population from differences in knowledge, backgrounds and experience (Pagliacci *et al.* 2020). The active stakeholders may be influenced with their previous engagement with private initiatives. Nonetheless, while the alternatives here are each presented as unique and separate policy strategies, one would expect that private green infrastructure would be reflected with the high preference placed on public green infrastructure to create a comprehensive citywide blue-green network.

The analysis shows there is consensus on the most optimal strategy focusing on public green infrastructure projects, with the least optimal being grey infrastructure in most cases, which is supported by the best practice literature of moving from grey to green solutions for water management. Government streamlining also emerges as a near consistent second ranked alternative which underscores the need for good governance to be able to tackle emerging climate adaptation problems. However, differences in the rankings emerge in the regional TOPSIS analyses demonstrating that there is not an internationally agreed upon hierarchy of adaptation strategies. The question for each city then becomes which additional policies best support this green and blue-green infrastructure. The other four alternatives can each be paired with public green infrastructure, but local knowledge and characteristics play a role in determining the strategy which is reflected through the criteria weights and alternative scores. Therefore, the results propose moving to incorporate a loose framework over a strict international guideline to foster the development and support of green and blue-green infrastructure over grey infrastructure as a principle solution as this approach allows for flexibility for supporting adaptation alternatives while providing a guidance basis to pull resources together and give cities confidence in their decision-making.

3.3.3. Sensitivity of the results

In the sensitivity analyses, here the chapter explores the stability of the TOPSIS scores across the three geographic regions and the full data set by examining the changes in criteria weighting to the four main criteria. The research focuses on the regions as they share similar criteria weight structures but differing alternative score hierarchies. In the four sensitivity analyses, the TOPSIS scoring remains relatively stable but is still subject to changes. North America presents the least sensitive results considering any of the alternative rankings across the criteria weight changes (fig. 3.1). While the rankings do change, they don’t occur until at larger criteria percentage changes around ±50%. The European region demonstrates the most sensitive criteria considering the top ranked alternative with weight changes of the criteria between -20 to +30% altering the position of public green infrastructure (fig. 3.2). The shift in the first and second ranking are more a response of public green infrastructure to the criteria weight adjustment than government streamlining.

In Europe (fig. 2) and Australasia (fig. 3.3), six alternative positions changes within the same criteria weight change of ±10-20%: 1st and 2nd for European political, environmental and social, 4th and 5th for European social and 3rd and 4th for Australasian political and economic. While these shifts do not occur at the smallest percentage shift ranges (>5%), the concentration of rank changing at low percentages indicates that while small individual shifts in perceptions will unlikely change the result, mild adjustments in attitudes or collective shifts can alter the final performance of the alternatives. When all the participants are aggregated together, the sensitivity is more muted (fig. 3.4). This indicates that a global, uniform adaptation guideline may mask the specific dynamics of a region, also considering the data set is skewed towards the least sensitive North American region, and it supports the idea of a loose framework that is adaptable to local characteristics.

Using the full aggregated data set, a further sensitivity analyses was performed considering the sixteen sub-criteria and their global weights. Despite the four main criteria sensitivity leading to shifts in alternative rank, no rank shifts occur for first rank, Public Green Infrastructure, second rank, Government Streamlining and fifth rank, Grey Infrastructure Overhauls. Additionally, the shifts between third and fourth rank, Private Green Infrastructure and Maintaining Urban Environments only occurs in nine of the sub-criteria at large variations in the weighting (+/-90% +). Six sub-criteria demonstrate no rank shifts at all: Implementation Time (political), Private Costs and Funding Availability (economic), Stormwater Capacity and Stormwater Quality (environmental), and Civic Engagement (social). None of the sixteen sub-criteria have an oversized effect on the ranking of the alternatives compared to the classification and grouping of the criteria.

These sensitivity results further indicate that public green infrastructure remains a relatively strong, top performing alternative. However, the sensitivity of some of the alternatives at low weight percentage changes makes it difficult to present a fully structured alternative hierarchy as small changes in input information, such as using reality based quantitative instead of hypothetical and theoretical values, or additional stakeholders might shift the position of the five alternatives.

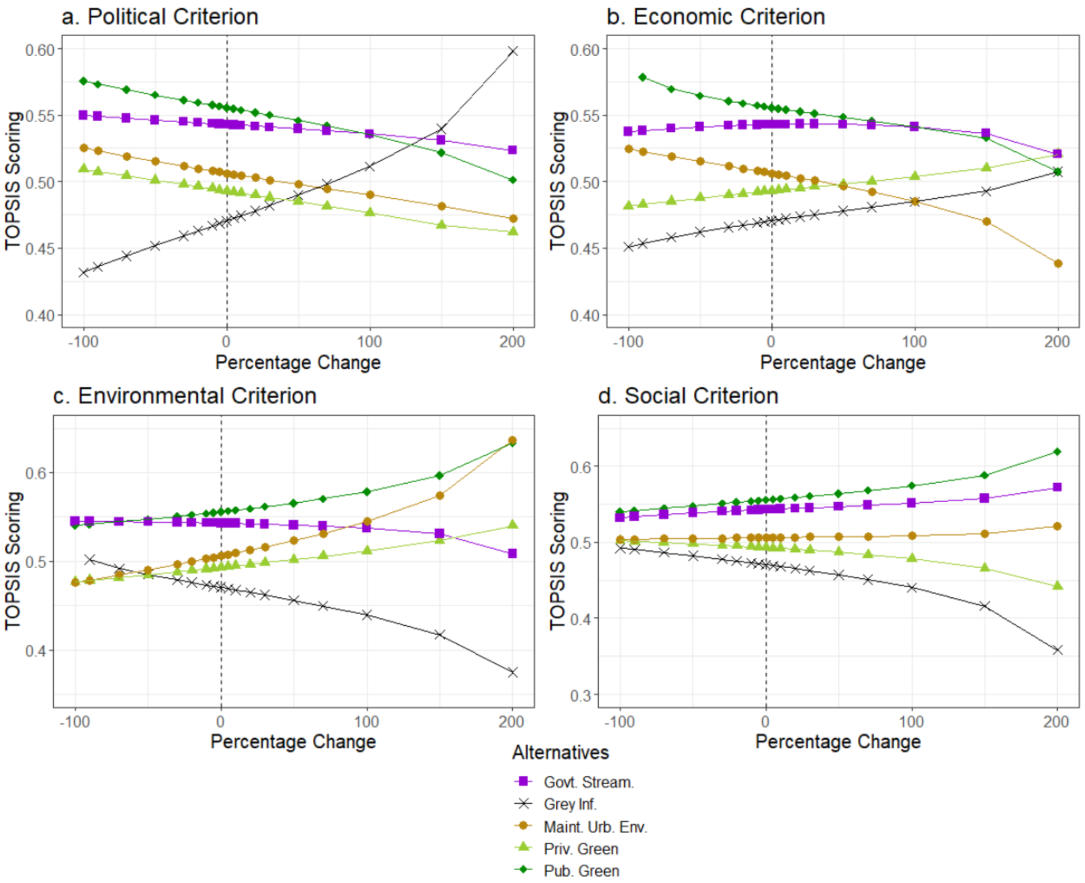

Figure 3.1: Sensitivity Analysis of all the North American participants and the alternative scoring by testing the percentage shifts in the four main criteria weights: a. political, b. economic, c. environmental and d. social with government streamlining (govt stream), grey infrastructure overhauls (grey inf), maintaining urban environments (MUE), private green infrastructure (priv. green), and public green infrastructure (pub. green).

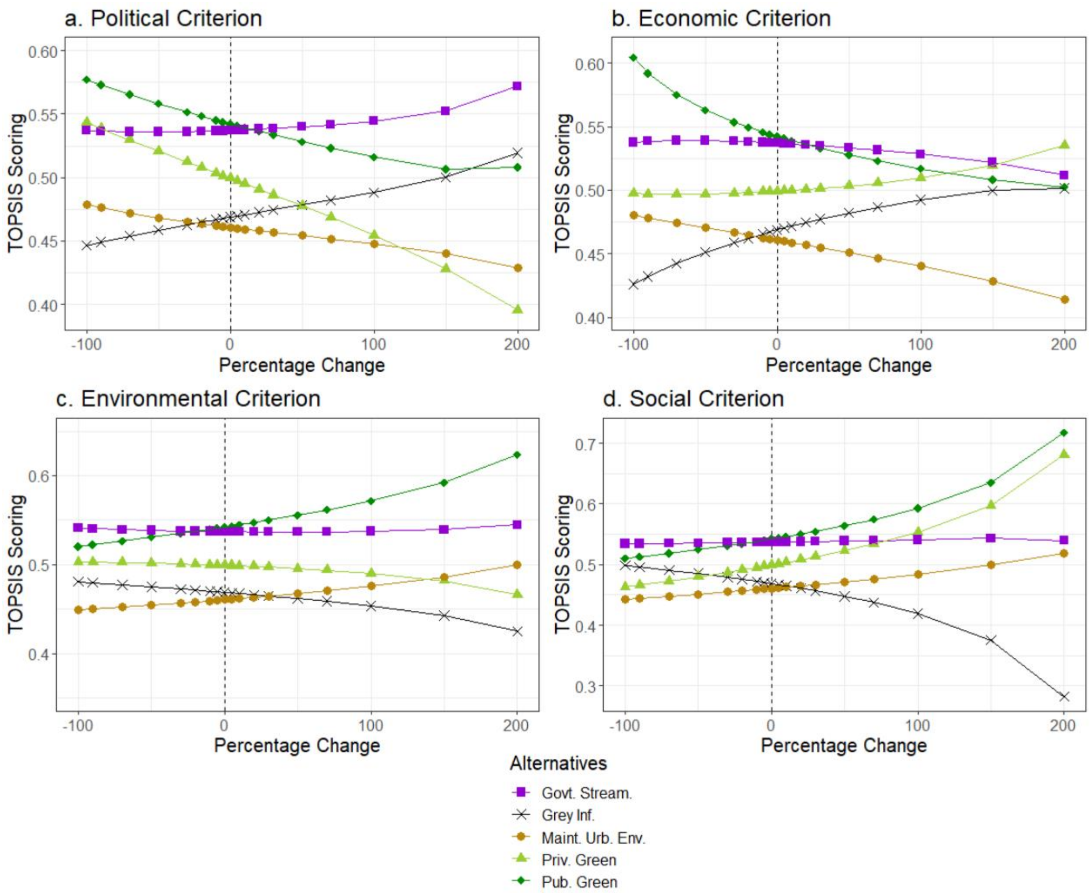

Figure 3.2: Sensitivity Analysis of all the European participants and the alternative scoring by testing the percentage shifts in the four main criteria weights: a. political, b. economic, c. environmental and d. social with government streamlining (govt stream), grey infrastructure overhauls (grey inf), maintaining urban environments (MUE), private green infrastructure (priv. green), and public green infrastructure (pub. green).

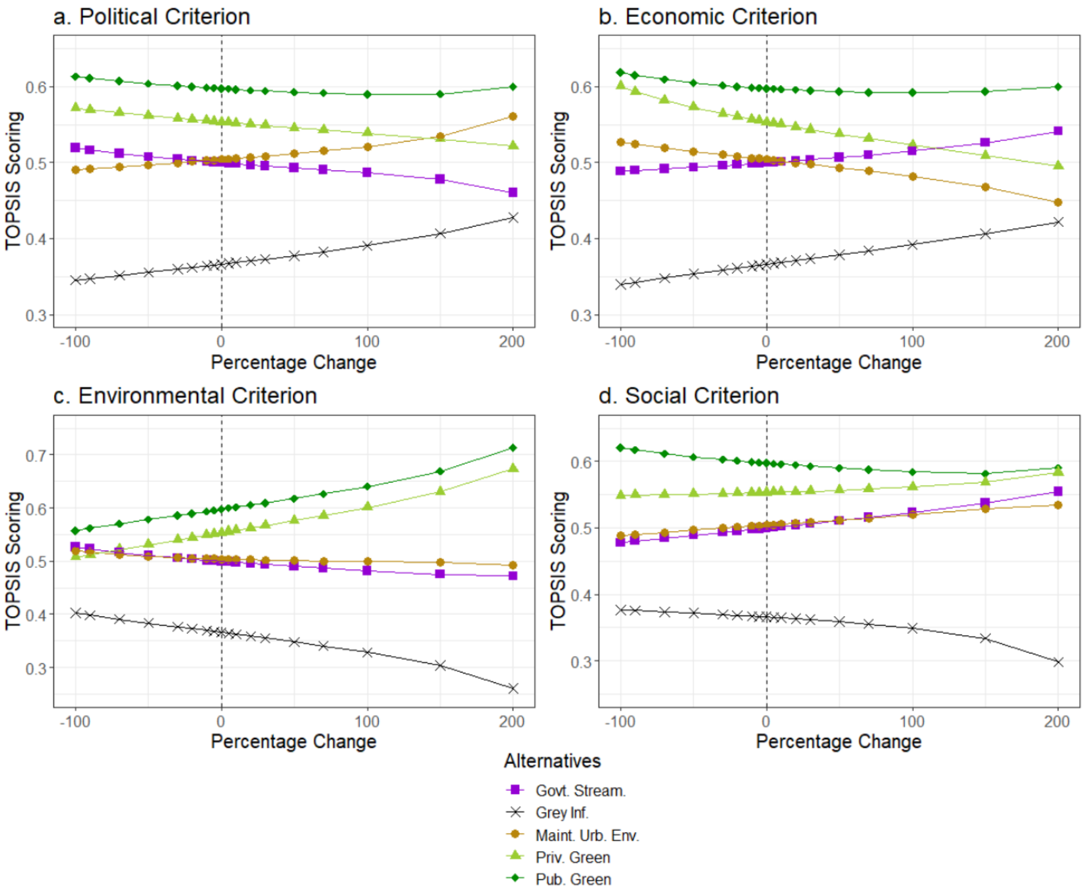

Figure 3.3: Sensitivity Analysis of all the Australasian participants and the alternative scoring by testing the percentage shifts in the four main criteria weights: a. political, b. economic, c. environmental and d. social with government streamlining (govt stream), grey infrastructure overhauls (grey inf), maintaining urban environments (MUE), private green infrastructure (priv. green), and public green infrastructure (pub. green).

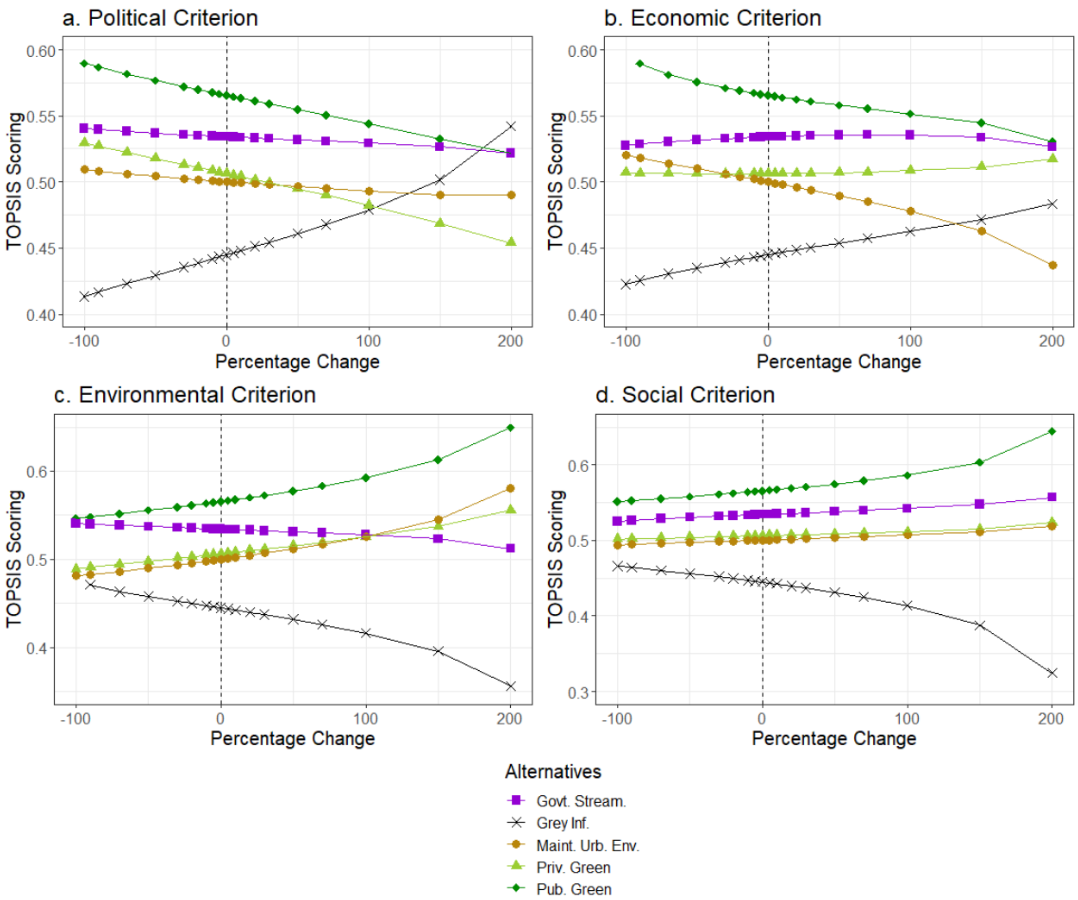

Figure 3.4: Sensitivity Analysis of all the 34 study participants and the alternative scoring by testing the percentage shifts in the four main criteria weights: a. political, b. economic, c. environmental and d. social with government streamlining (govt stream), grey infrastructure overhauls (grey inf), maintaining urban environments (MUE), private green infrastructure (priv. green), and public green infrastructure (pub. green).

3.4. Chapter Conclusions

This chapter has successfully identified four major trends in the perceptions of future stormwater management under climate change.

First, the research demonstrates that the emerging theoretical focus on ecological, social and new economic criteria within climate change management are still underweighted compared to the traditional political, cost-based and quantitative importance of policy management. The consequences of these different approaches in policy can hinder the ability to push through much needed climate change legislation and increase dissatisfaction with the policy system.

Second, principally throughout the surveys, public green infrastructure is the preferred alternative to manage future rainfall and pluvial flood adaptation projects across the six cities despite differences in the criteria weightings. This finding coincides with green infrastructure emerging as a best management practice tool for stormwater management in existing urban policy discussions, as previously explored in Chapter 1.

Third, grey infrastructure is nearly universally the least preferred adaptation method. Again, this counters the theoretical discussions on stormwater management where grey infrastructure is frequently acknowledged as being necessary in future adaptation projects as explored in Chapter 1.

Fourth, there is a lack of uniformity in the alternative rankings when the cities are organized by region. Therefore, the research supports that a loose international framework can be established prioritizing public green infrastructure, but that local knowledge and regional considerations retains an important role in adaptation so that a full international hierarchy standard cannot be adopted.

Future work is required to understand if there is a universally preferred alternative to support green infrastructure or if local needs determine the supportive tool. Regardless of if uniformity exists, our own cultures will influence how we adapt (Adger *et al.* 2012). Therefore, we should question if we wish to sacrifice local knowledge in favor of an international homogenous approach (Rosenzweig *et al.* 2019). Nonetheless, the loose framework is still beneficial towards the international community. Many cities lack the resources of the six large, wealthy and global cities that were the basis of this study. However, the pressures of adaptation persist and this guidance away from grey infrastructure towards green infrastructure ensures that these municipalities are making decisions based off the time and resources of these mega-cities. As decisions need to be made in increasingly shorter time periods, the confidence in the decisions is increased if they can be based on an agreed approach to adaptation. This is increasingly important for rapidly growing urban areas in the developing world who require new infrastructure to protect both formal and informal settlements.

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Appendix 3.1 Survey User Guide

WELCOME!

Thank you for participating in the stakeholder survey for the doctoral thesis *Adaptation through Policy: Climate Change induced heavy rainfall events and flash flooding*. Your input is an integral and valuable part of the research in determining the global trends in urban policy regarding rainfall and stormwater management. Your response will join responses from three different stakeholder groups: Formal City Governance, Research, and Advocacy and Conservancy (selected from a focus group study) across six developed coastal cities: Copenhagen, Amsterdam, New York City, Vancouver, Sydney (City of Sydney), and Auckland to provide an in-depth look at policy trends towards stormwater management.

The main question we are trying to answer is: what is the best way to reduce flooding from heavy rainfall events in cities, understanding that climate change will make these occurrences more frequent? We are interested in overland flooding from rainfall; we are not exploring river or coastal flooding. Using your city's existing policies, guidebooks, and legislations we have outlined what criteria is important when cities try to answer this question. This paper is published at the *Journal of Environmental Planning and Management*: https://doi.org/10.1080/09640568.2020.1823346. Afterwards, using the same documents, we established which criteria are the most important when discussing these stormwater adaptations.

WHAT WILL YOU BE DOING?

Stage 1: Comparing the criteria

Before deciding which policy to implement we will first establish how important are the criteria. At the highest level, cities have POLITICAL, ECONOMIC, ENVIRONMENTAL, and SOCIAL considerations when making decisions on rainfall stormwater flooding. Using the following scale, you will be comparing these four criteria together for how important they are when answering the rainfall problem:

Comparisons	***Meaning***
Equally Important	*Both options have equal importance*
Moderately More/Less Important	*Using experience and judgement, one option is slightly preferred over the other*
Strongly More/Less Important	*Using experience and judgement, one option is strongly preferred over the other*
Very Strongly/Demonstratively More/Less Important	*Using experience and judgement, one option is very strongly preferred over the other. This option has demonstrated preference over the other in practice*
Extremely/With Certainty More/Less Important	*Using experience and judgement, one option is extremely preferred over the other. This option has demonstrated preference over the other in practice to the highest degree of certainty*

Each of these criteria will have sub-criteria that make it important. For example, to make an ECONOMIC decision you must consider the public costs but also the private costs. *See A1 for the full list of sub-criteria.* You will then be asked to compare these sub-criteria together for how important they are to their criteria when solving the rainfall question, example: how important are the public costs compared to the private costs when considering the economic criteria of preventing stormwater flooding?

Stage 2: Rating the alternatives

Now that the comparisons are done, you will be rating five different policy solutions or ‘alternatives’ to preventing rainfall flooding. *See A2 for the full list of alternatives!* Using the different linguistic scale below, you will be rating how well each of the alternatives performs or satisfies the sub-criteria.

Ranking	***Meaning***
Very Low	*Using experience and judgement, the alternative has a very low ability to satisfy the requirements of the criterion.*
Low	*Using experience and judgement, the alternative has a low ability to satisfy the requirements of the criterion*
Moderate	*Using experience and judgement, the alternative has a moderate ability to satisfy the requirements of the criterion*
High	*Using experience and judgement, the alternative has a high ability to satisfy the requirements of the criterion*
Very High	*Using experience and judgement, the alternative has a very high ability to satisfy the requirements of the criterion.*

We recognize that in practice, some criteria can be viewed as interdisciplinary and some alternatives are implemented in parallel. However, please approach the criteria and alternatives of Appendix 1 and 2 as theoretically independent of each other.

SAVING PROGRESS AND FINISHING

You will then have finished the survey! *Below follows a reference guide while completing the survey outlining the criteria, sub-criteria and alternatives. Please reference it as needed!* **YOU CAN SAVE YOUR SURVEY PROGRESS AND RETURN AT ANOTHER TIME**. You are able to save and return to this project at any time before submitting your responses. Follow the instructions of the save button to save your responses and you will be able to re-enter the survey with the link sent to your email. Your responses will be saved. Finally, your responses are based on your own opinions. They do not have to align with current existing legislation but are guided by your own experience and expertise in the field. Your responses will be analyzed anonymously.

Thank you!

A1: The Criteria and Sub-Criteria

Criteria

Political	This criterion is concerned with political ability, actions and concerns regarding policy management. It includes the legislative and political framework for making decisions as well as the ability to execute policy.
Economic	This criterion is centered around the financial considerations and concerns regarding policy management. This captures the costs and savings of both public and private financing as well as industrial engagement.
Environmental	This criterion focuses on the environmental responses and needs in policy management. It includes the ecological components of water and environmental management in the city as well as the connections to climate change.
Social	This criterion captures the social and urban functionality in policy management. It includes the actions of citizens and policies' effects in daily life while also considering the social benefits of urban management.

Political Sub-Criteria

Existing Legislative Framework	The existing laws, regulations and directives in the city that set the basis and allow for the further development of stormwater management policies
Project Feasibility	The political will, planning framework and technical skills available to the city to implement new policy and management alternatives
Jurisdiction	The city's ability to directly implement and manage policy relating to stormwater through control and input over the responsible agencies or departments

Implementation Time	The timeframe for a policy or management alternative from proposal through implementation

Economic Sub-Criteria

Public Costs	The construction and maintenance costs of an alternative that the city or public body pays for
Private Costs	The construction and maintenance costs of an alternative that private entities or individuals pay for
Funding Availability	The availability of funding from internal, local, regional, national or international bodies to help with costs
Green Industry Growth	The ability for the environmental business and governmental sectors that focus on green technologies, services and products to develop and grow while focusing on a policy alternative

Environmental Sub-Criteria

Stormwater Capacity	The ability of an alternative to manage stormwater volumes
Stormwater Quality	The ability of an alternative to manage the water quality of stormwater by managing and removing pollutants
Ecosystem Support	The capacity of an alternative to support healthy, local, biodiverse ecosystems in the city
Energy Usage	The energy consumption required by an alternative from construction through management

Social Sub-Criteria

Risk to Human Health and Safety	The potential for the alternative to pose dangers to the public directly or indirectly during the life cycle of the alternative such as construction dangers, road use dangers, contaminated water, etc.
Civic Engagement	The ability and willingness for citizens to engage in policy management and take initiative in adaptation strategies from the proposal stage through the implementation of the alternative
Reducing Inequalities	The extent the policy provides opportunities to reduce urban inequalities, example: economic, access to healthcare, access to environment, etc. and provides the potential for local employment
Synergies with other Adaptations	The extent the policy contributes to overall urban health and protecting against other hazards to urban populations, example: pollution, air temperature, drought, etc.

<u>Please note that some of the sub-criteria are positive and some are negative. However, rate them on the same scale. For example, an alternative could have HIGH public costs (a negative attribute) but HIGH ecosystem support (a positive attribute). Similarly, an alternative could have LOW risk to human health (negative attribute) but LOW stormwater capacity (positive attribute).</u>

A2: The Policy Alternatives

Policy Alternatives

Grey Infrastructure Overhauls: This policy alternative attempts to transform and expand existing stormwater systems using grey infrastructure. These structures are traditionally built of concrete and include but are not limited to treatment facilities, sewage systems, pipping, stormwater systems, combined-sewage overflows (CSOs). For example, this alternative frequently exhibits itself in policy documents as attempts to separate stormwater and sewage shed, expand treatment facilities, expand system capacity, and move water away from the city.
Public Green Infrastructure: This policy alternative is concerned with green infrastructure regarding public management. Green infrastructure can be used as both stormwater retention and stormwater infiltration. In retention, stormwater is stored and released slowly to not overwhelm stormwater systems. In infiltration, stormwater is brought back into the soil. Green infrastructure can take many forms. Tree beds, rain gardens, rain barrels, cisterns, green roofs and architecture, swales, constructed marshland and berms are examples of green infrastructure. Permeable pavement is another example. Rain ponds include both natural ponds and flexible urban space that are allowed to flood. This alternative also includes ‘blue infrastructure’ which is specifically regarding water management such as reconstructing historical stream and river networks. This alternative applies to both large scale city projects and small managed city spaces and buildings.
Private Green Infrastructure: This policy alternative is concerned with green infrastructure that is financed and installed through private citizens and businesses. The same infrastructure applies as with public green infrastructure. This alternative can scale from property developers to individual homeowners.
Government Streamlining: This alternative is centered on the bettering of government systems. City governments can join responsibilities and foster collaborative participation between agencies that manage water, stormwater and green spaces. Better comprehensive management policy is better directed towards solving cloudburst management and provides better oversight in managing targets. Cities also continue to publish guiding documents outlining their plans, goals and targets. This policy encourages cities to make clear the laws, regulations and options for both civil servants as well as citizens when it comes to cloudburst management. Governments can also develop specific emergency management plans to mitigate flooding events.
Maintaining Urban Environments: This policy alternative is focused on ensuring the city is better prepared to handle cloudburst events. Reducing street litter ensures that stormwater systems both grey and green operate optimally. Protecting wastewater

treatment plants from flooding ensures the stormwater system operates under high stress conditions. Cities also have options available in land use planning to help redeveloped brownfield sites, encourage healthy growth, and discourage growth in high vulnerability areas. The alternative ensures that stormwater systems operate efficiently while trying to decrease the risk of the urban environment to flooding.

Appendix 3.2 Raw Data

Table A3.2.1: Group aggregated by consistency non-normalized weights for the main criteria

		Participant Grouping						
		Total Participants	Governance	Advocacy	Research	N. America	Europe	Australasia
Main criteria (weighted)	Pol	1.30885	1.37558	1.55680	1.12950	1.31912	1.34735	1.25181
	Econ	1.12639	1.42857	0.94249	0.98046	1.08277	1.52886	1.00397
	Env	0.89612	0.86860	0.64418	1.11293	0.88286	0.88212	0.94697
	Soc	0.7569	0.58586	1.05710	0.81136	0.79302	0.55033	0.84024

Table A3.2.2: Group aggregated by consistency non- normalized weights for the sub-criteria

Main Crit.	Sub-Crit	Participant Grouping						
		All	Governance	Advocacy	Research	N. America	Europe	Australasia
Pol	ExLF	1.050242	1.050483	1.009728	1.08424	1.123344	0.818002	1.168196
	ProjF.	1.379081	1.096756	1.881574	1.643667	1.225079	1.350252	2.305398
	Juris	1.049462	1.30648	0.954583	0.751507	1.148522	0.850967	1.000297
	ImpTime	0.657891	0.664352	0.551392	0.746669	0.63268	1.063942	0.371201
Econ	PubCosts	1.796779	2.022308	1.641036	1.715741	1.839982	1.670476	1.776326
	PriCosts	0.891408	1.022024	0.801006	0.846279	0.764562	1.355881	0.994755
	FundAv	1.331565	1.229846	1.616169	1.255016	1.271105	1.177614	1.637196
	GIG	0.468885	0.393406	0.470717	0.548764	0.559233	0.374917	0.345669
Env	StormCap	1.524715	1.752109	1.062154	1.608086	1.165836	2.466	2.188
	StromQua	1.111821	1.175901	1.332934	0.935917	1.272011	0.801905	1.02346
	EcoS	0.98715	0.868294	1.021298	1.122265	0.972465	1.139104	0.881299
	EnU	0.597576	0.558986	0.691595	0.59205	0.693421	0.443936	0.506709
Soc	RiskHHS	1.915801	1.729716	2.346846	1.894144	1.804662	1.229278	2.925593
	CivEng	0.788778	0.703439	0.851981	0.875831	0.759048	1.041387	0.774546
	RedIneq	0.727661	0.774263	0.864679	0.581545	0.829138	0.554475	0.547323
	SynAd	0.909422	1.061477	0.578403	1.036533	0.880457	1.408822	0.806298

Table A3.2.3: Group aggregated TOPSIS distance from ideal positive (S^{+}) and negative (S^{-}) solution and closeness coefficient (C^{*}) of the policy alternatives

			Policy Alternatives				
			Grey Inf.	Pub Green	Priv Green	Govt Stream	Maint. Urb. Env.
Participant Grouping	All	S^{+}	0.230665	0.174632	0.199653	0.186028	0.19667
		S^{-}	0.184878	0.227296	0.204686	0.213305	0.196725
		C^{*}	0.444907	0.565514	0.506225	0.534154	0.500069
	Governance	S^{+}	0.232896	0.177847	0.215516	0.198401	0.199202
		S^{-}	0.205854	0.233817	0.208471	0.230194	0.209241
		C^{*}	0.469183	0.567981	0.491692	0.53709	0.512289
	Advocacy	S^{+}	0.225213	0.161315	0.181688	0.157504	0.185534
		S^{-}	0.145136	0.209841	0.185268	0.201355	0.179348
		C^{*}	0.39189	0.565371	0.504878	0.561098	0.491523
	Research	S^{+}	0.230639	0.172494	0.193365	0.18438	0.195094
		S^{-}	0.188253	0.232931	0.208036	0.204305	0.194995
		C^{*}	0.449407	0.574535	0.518275	0.525631	0.499874
	North America	S^{+}	0.219565	0.177902	0.203183	0.181526	0.193038
		S^{-}	0.195114	0.222475	0.19757	0.215649	0.197892
		C^{*}	0.470519	0.555664	0.492996	0.542957	0.506208
	Europe	S^{+}	0.234297	0.182192	0.204206	0.186555	0.209358
		S^{-}	0.206722	0.215731	0.203547	0.216435	0.178808
		C^{*}	0.468738	0.542142	0.499192	0.537073	0.460648
	Australasia	S^{+}	0.255092	0.166696	0.183874	0.204727	0.202898
		S^{-}	0.14732	0.247325	0.227748	0.204469	0.206086
		C^{*}	0.366093	0.597373	0.553294	0.499685	0.503897

Thesis Conclusions

The thesis has successfully analyzed the current and future directions of urban stormwater management under the threat of climate change induced heavy rainfall events. In particular, I identify four main conclusions within the thesis. These conclusions help shed light on the future direction cities are taking stormwater management and how to better adapt to an increasing frequency of heavy rainfall intensities in urban areas.

First, considering the six case cities: New York City (NYC), Vancouver, Copenhagen, Amsterdam, Sydney and Auckland, cities are taking an active role in planning for stormwater management. While the justification of these management plans differs based on the cities' unique geographies, circumstances and needs for water, there emerge some unifying trends in the narrative of management. Principally, public green infrastructure is held as best management practice for the future of stormwater management amongst five unique policy alternatives: public green infrastructure, private green infrastructure, grey infrastructure overhauls, maintaining urban environments and government streamlining. By connecting both into the green city and sustainable city narratives, green infrastructure can solve multi-urban problems while directly aiding stormwater management. However, the discussion around green infrastructure does not come at the expense of the continued need, albeit not desire, for grey infrastructure to continue to have a role in stormwater management due to the differences in capacity between the two infrastructure types. Green infrastructure might be the most preferred option theoretically but the limitations and uncertainties around capacity continues the need for traditional grey stormwater systems.

In discussing the new directions of stormwater management, cities are embracing criteria for decision making that differ from traditional infrastructure considerations. While political and economic decision criteria such as the costs, timing and technical capacities of stormwater infrastructure will always be important in this decision making, cities are embracing new and emerging social criteria with focuses on justice and equity in their decisions as well as environmental considerations encompassing the benefits and tradeoffs of new policies and constructions. These new criteria have grown in importance with the development of climate change literacy amongst the general public and policy makers, integrating within daily urban life decision making such as stormwater adaptations.

Second, when eliciting the opinions from three stakeholder types involved in stormwater management within the cities: researchers, policy makers and activists, these first conclusions are often contradicted. Public green infrastructure projects continue to form the most preferred option for stormwater management across the cities and stakeholders demonstrating that the desire for these projects is not just theoretical but also observed in practice. However, grey infrastructure is viewed as being the least satisfactory alternative to manage future stormwater inundations. This directly contradicts the discussed need for this alternative as those stakeholders rate it poorly against the criteria in stormwater decision making. This disconnect could lead to dissatisfaction within policy making if grey infrastructure projects are implemented yet unpopular, risking alienating stakeholders from urban policy discussions. Additionally, ignoring grey infrastructure to satisfy stakeholders might leave cities vulnerable to high intensity rainfall events without the proper facilities to manage the volume of water.

The traditional political and economic criteria considerations surrounding stormwater infrastructure continue to hold more importance than the emerging environmental and social criteria based in climate change discussions when considering the stakeholder responses. This confirms that public green infrastructure performs well in the traditional decision-making environment but further demonstrates grey infrastructure's unpopularity. As grey infrastructure is a traditional legacy policy alternative, it no longer performs well within the traditional criteria considerations. Additionally, the differences between the observed priorities of the emerging social and environmental criteria versus their theoretical discussion risks disconnecting the reality of decision making from policy discussions. While the discussions around climate change and stormwater management have evolved, the demonstrated reality of policy criteria has not, and this gap can further disenfranchise important stakeholders in the decision-making process.

Third, due to these differences in the theoretical discussions around stormwater management and the analyzed data, as well as differences emerging within the analyzed data, the thesis recommends that cities looking to adapt to heavy rainfall events should principally approach green infrastructure projects, but that their own local needs and characteristics prevent the establishment of a full adaptation guidebook or hierarchy. Additionally, cities should not ignore grey infrastructure projects despite their unpopularity. However, cities can confidently move forward with adaptation projects knowing that this loose framework is based on the expertise of these six global and forward-looking cities.

Fourth and finally, the thesis has come to these conclusions by implementing a combined Analytic Hierarchy Process (AHP)- Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) multi-criteria decision analysis (MCDA). MCDAs are well established within policy making, however, their use is often restricted to experts with knowledge of their internal mechanics. Here, the AHP-TOPSIS methodology has been presented in an accessible manner while connecting to the established theoretical discussions thus allowing multiple non-expert stakeholders to engage directly with the MCDA. This engagement can increase the trust in the process and allow stakeholders to feel more empowered in their decision making. The method is particularly useful in stormwater and other climate change adaptation projects, as it easily and quickly integrated both quantitative, qualitative, and uncertain judgments and data while producing a quantitative output directly useful for policy making. Additionally, it allows for the data to be organized as desired to enable decision makers to observe how the results of the MCDA would change based on the location of certain participants or the type of participants. This can allow for more inclusive policy making and helps open the discussion between sometimes conflicting stakeholder opinions.

The conclusions from this thesis have clear implications for urban stormwater adaptation policy but also contribute to the respective literature within the science and management of climate change, providing the basis for future research. Methodologically, the thesis' integration of existing MCDA methods provides a useful case study on the viability of these methods within climate change decision making. By successfully integrating the components of the complex and interdisciplinary nature of climate change decision making, the thesis encourages future work to be undertaken with additional MCDA methods to test their viability within this decision framework. Within climate change and water management, the methodology can be extended to examine the political and engineering adaptations to additional water risks such as fluvial flooding and sea level rise. The methodology can further be extended to examine multidimensional climate change adaptations such as urban heat waves paired with drought as well as the multidimensional aspect of certain adaptation alternative's ability to answer multiple problems, for example green infrastructure. In this way the methodology can help identify adaptation alternatives that are most preferred to respond to multiple urban climatic shifts thus increasing the adaptative capacity of urban areas. The accessible nature of the presented MCDA, as well as the focus on stakeholders, has contributed to the discussions of science communication and encourages additional research to consider the approachability of methods to increase decision transparency. While there is no correct MCDA method for a given decision, the type of data a decision maker has may be more suited for different methods and it is important that all stakeholders involved have the opportunity to understand how the decision is being made.

The thesis findings have contributed to the theoretical discussions around the ideals of climate change management, governance and society versus the reality of implementing these options. By contextualizing and observing the different values held by the stakeholder groups compared to each other as well as the existing policy documents, future sociological work can focus on understanding the reasons these differences emerge. Additionally, future work should understand if these reasons can be modelled and thus more easily integrated in future adaptation decision making studies. The development and integration of a happiness or satisfaction indicator alongside policy alternatives can additionally ensure policy decisions maximize stakeholder satisfaction even when the preference for decision alternatives differ between the groups. Future work in this direction will also facilitate better science communication between stakeholder groups as well as experts and the general public.

Specific towards urban pluvial flood adaptation management, future work should consider what conditions could trigger the preference for one of the adaptation alternatives over the other. Research in this direction could then construct a theoretical guidebook for the adaptation alternatives, highlighting when they would be considered preferred. This can then be modelled alongside the site-specific qualifications, such as cost, flow rate, etc. of site studies to help ensure that optimal adaptation alternatives are selected during the decision-making process and that future policy makers as well as researchers can reference the alternatives and their specific conditions. Modelling these conditions would also allow researchers and practitioners in civil engineering and urban planning account for the variability in climate predictions and urban development scenarios. This in turn would allow cities to project the long-term adaptation requirements of urban areas as well as help modify the alternatives to account for the future requirements of adaptation. Work in this direction would also be beneficial towards developing cities; it would provide additional guidance on adaptation alternatives to study within specific local projects.

Finally, this work has focused on large, developed cities in North America, Europe and Australasia. Similar studies, regarding pluvial flood adaptation management should be conducted within developing cities as well as within non-westernized cities to observe if there are differences between these urban systems and their stormwater management plans. The unique histories and development patterns, as well as the need to implement infrastructure as opposed to retrofitting a whole system, may alter the overall preferences towards certain policy alternatives. These cities may also provide new alternatives not considered by the developed cities that would be beneficial to pluvial stormwater management within their built environments.

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Io sottoscritto Charles Axelsson

nat o. a Islanda (prov. EE) il 6 Febbraio 1994

residente a New York in 36th Street n. 120

Matricola (se posseduta) 956389 Autore della tesi di dottorato dal titolo:

Asessing Urban Policy Adaptations to Pluvial Flooding and Stormwater Management under Climate Change

Dottorato di ricerca in The Science and Management of Climate Change

(in cotutela con ……………………………………………)

Ciclo 33

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Studente: Charles Axelsson matricola: 956389

Dottorato: Science and Management of Climate Change

Ciclo: 33

Titolo della tesi[1] :Assessing Urban Policy Adaptation to Pluvial Flooding and Stormwater Management Under Climate Change

Abstract:

Italiano:

Il numero crescente di nubifragi osservati di recente nelle aree urbane rischia di causare notevoli perdite sui sistemi economico, sociale e ambientale. Nonostante alcune città prendano decisioni riguardo alle misure di contenimento degli impatti delle acque piovane, non è sufficientemente chiaro se queste decisioni seguano uno schema comune nell'elaborazione di modelli che aiutino le città ad affrontare simili adattamenti in futuro. Questa tesi è strutturata in tre capitoli, basati su tre pubblicazioni. Il primo esplora le politiche di gestione delle acque piovane implementate dalle sei città prese come campione di riferimento. Il secondo sviluppa una metodologia combinata di Multi-Criteria Decision Analysis di Analytic Hierarchy Process (AHP) e Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) per analizzare le opinioni di stakeholders interessati al processo decisionale per la gestione delle acque piovane. Il terzo usa la metodologia AHP-TOPSIS per valutare le percezioni degli stakeholders riguardo i metodi di gestione delle acque piovane nelle sei città, al fine di analizzare il consenso tra i diversi approcci.

English:

Increasing frequencies of heavy rainfall events in urban areas threaten to disrupt urban systems causing political, economic, social and environmental loses and damages. While cities make stormwater adaptation decisions, little is known if these decisions follow a similar pattern so that an adaptation framework can be developed to help cities facing similar stormwater adaptations in the future. The thesis is structed in three chapters based on three published articles. The first chapter explores the existing state of stormwater adaptations and the existing policy frameworks to make these decisions in six global and developed cities. The second chapter develops a combined Multi-Criteria Decision Analysis of the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to analyze the opinions towards stormwater management from select stakeholders with interest in the decision-making process. The third and final chapter uses the AHP-TOPSIS methodology to evaluate the opinions around stormwater management amongst the stakeholders in the six cities to identify if a decision hierarchy exists.

Charles Axelsson 08/12/2021

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