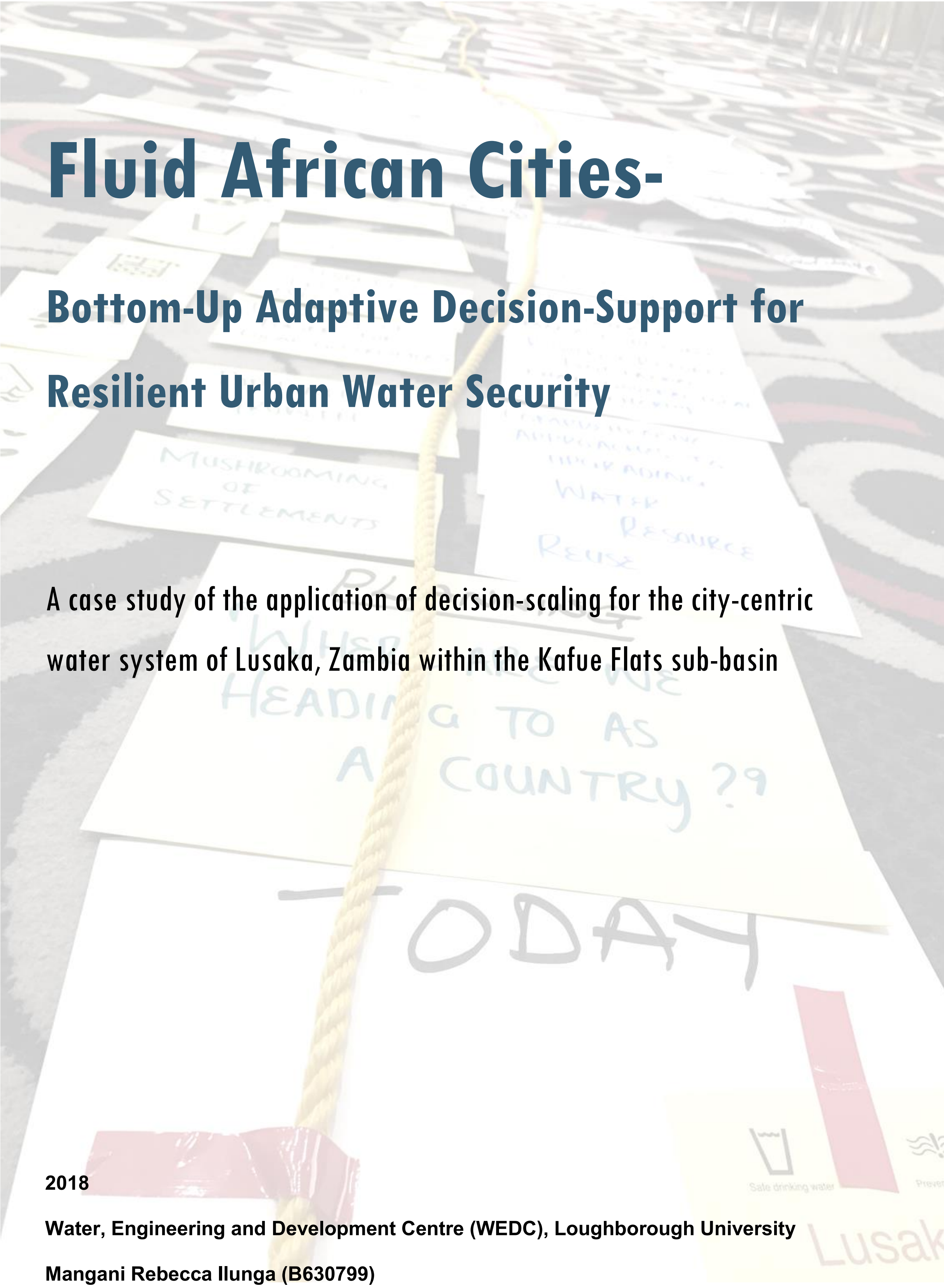

Fluid African Cities-

Bottom-Up Adaptive Decision-Support for Resilient Urban Water Security

A case study of the application of decision-scaling for the city-centric water system of Lusaka, Zambia within the Kafue Flats sub-basin

2018

Water, Engineering and Development Centre (WEDC), Loughborough University

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Fluid African Cities- Bottom-Up Adaptive Decision-Support for Resilient Urban Water Security

A case study of the application of decision-scaling for the city-centric water system of Lusaka, Zambia within the Kafue Flats sub-basin

by

M.R. Ilunga (B630799)

A research dissertation in partial fulfilment
of the requirements for the award of the degree of Master of Science (MSc)
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2018

Supervisor: Dr Lee Bosher

Key words: resilient water systems, decision-scaling, African IUWM, city-regional adaptation

Water, Engineering and Development Centre (WEDC),

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EXECUTIVE SUMMARY

RESEARCH BACKGROUND

Globally, the implications of climate change and rapid urbanisation are a growing concern for the future of water resource management. African cities are places with significant water security risk, rapid urbanisation and multiple spatial and temporal scales (UN-WWAP, 2009). Identifying these risks provides insights into where resilience is required, which allows for informed adaptation decisions. Water managers are accustomed to changing circumstances and adapting to them; however, uncertainties associated with climate and socio-economic changes create an additional layer of complexity. Decision-support tools used for the evaluation and management of water resources should reflect the potential impacts of these changes.

INTRODUCTION

Although the drivers of African climate change and urbanization is improving, there exists relatively little work on the links between climate change risks and urban development (Calow et al., 2011; Jones et al., 2014). The growth of cities includes the development of formal and informal water resources exposed to changing climates, environments, economies and demographics. To inform future investment and development decisions, a better understanding of the impacts of climate change and socio-economic variability on water, energy and food supply systems is required. The research investigates city-centric water security and the resilience of formalised urban African water supplies for a set of climate change and socio-economic risks, using a case study of the city of Lusaka, Zambia. The study area was the Kafue Flats, which includes the city of Lusaka (see **Figure 1**).

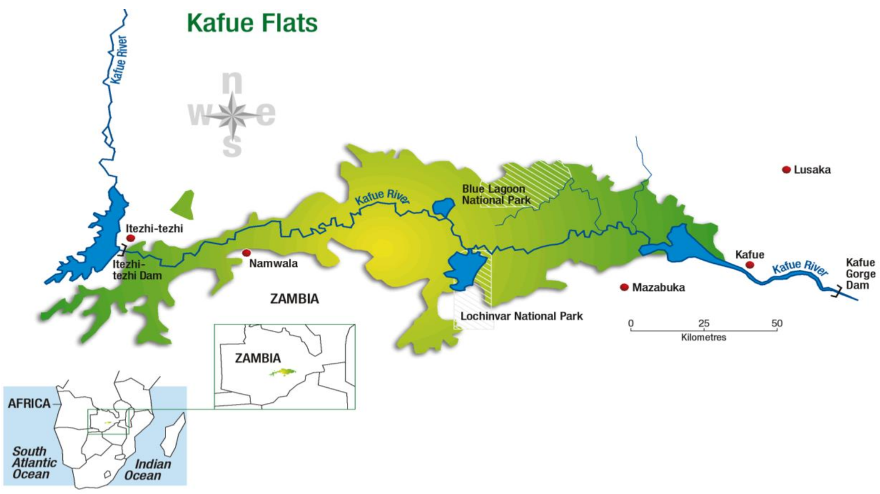

Figure 1: Study area (WWF, 2003)

The research aimed to investigate a city-centric approach to adaptive decision-support, to better inform African urban water system resilience to climate and socio-economic changes. The research objectives and related research questions are summarised in **Table 1**. Answering these questions using literature and a methodological approach has the potential to address ways in which urban water can be better managed in African cities and how the available resources and their development can be more resilient to a range of future uncertainties.

Table 1: Objectives and associated research questions

Objectives	Research questions
1. Explore city-centric water system and the climate and socio-economic sensitivities and uncertainties of the system at a city-regional scale.	1.1 What are the climate and socio-economic stressors to a city-regional water system? 1.2 How do city-regional sensitivities to change translate into city-centric impacts on a water system?
2. Quantify the vulnerabilities of African urban water security and its dependant sectors, due to external stressors, by developing a city-centric water resource model of the city of Lusaka reliant on the Kafue River Basin.	2.1 What are the dependent sectors of African urban water security? 2.2 How can the vulnerabilities of a water system, and its dependent sectors, be quantified to inform resilience?
3. Inform short to medium-term decision-making by evaluating the water system's vulnerabilities, using an adaptation framework for decision support.	3.1 How can vulnerable water systems be more resilient in the short to medium term? 3.2 What adaptation frameworks are used for water management decision support?

METHODOLOGY

The methodology included a literature review from a wide range of literature for existing water systems, their security and how they are managed. Management reviewed included that for water dependent sectors, specifically the water-energy-food nexus, and how the systems are impacted by climate and socio-economic changes. The literature reviewed water in African cities, and the adaptation required to ensure that the water systems are resilient to climate and socio-economic changes. The methodological approach was based on quantitative outputs.

Decision-scaling was used as a methodology to inform short to medium-term decision-support by evaluating the water system's resilience to climate and socio-economic system stressors. The decision-scaling framework is a bottom-up adaptation decision-support framework that identifies critical thresholds of a water system for a range of climate and non-climate (socio-economic) related future scenarios. Bottom-up adaptation approaches begin with stakeholder engagements to identify the system that needs to be investigated, which in this case was water. The approach then looks at the failure possibility of the system, and then evaluates these failure possibilities in the context of possible societies. In the final stages of these approaches, they identify possible climates likely to affect the modelled system. For decision-scaling the bottom-up approach is summarised in **Figure 2**; this was the approach used in the study, adapted from Poff et al. (2015).

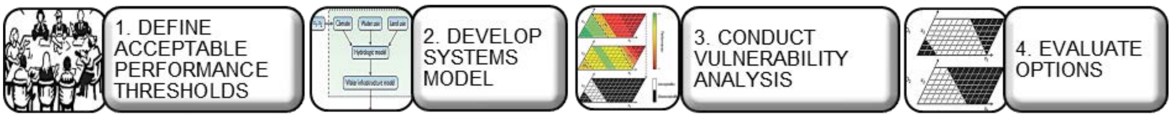

Figure 2: Decision-scaling framework used adapted from Poff et al. (2015)

THE RISK NARRATIVE OF LUSAKA AND THE KAFUE FLATS

Through a series of City Learning Labs in Lusaka, which are a platform for stakeholders' engagement, water and its security was identified as a critical focus area. A conceptual model of the Lusaka water system was developed using the Water Evaluation And Planning (WEAP) model by SEI, which was used to explore the system vulnerabilities to socio-economic and climate changes. The climate and socio-economic system stressors and the management scenarios modelled for both the city-scale and basin-scale are summarised in **Table 2**.

Table 2: Modelled water demand management scenarios and system stressors

Scale	Scenarios	Socio economic stressors	Climate stressors	Management scenarios	References
City	P1 (2017)	Population increase, non-revenue water decrease, and decrease in peri-urban population	City-scale (∆ regional MAR and ∆ regional MAP)	Upgrades to Kafue pipeline and increased borehole abstraction	(JICA, 2009; Millennium Challenge Corporation, 2011; Gauff Ingenieure, 2013)
	P2 (2020)				
	P3 (2035)				
Basin	P3H1 (2035 Baseline)	2035 socio-economic status of P3	Basin scale (∆ regional Temperature and ∆ regional MAP)	City scale 2035 scenario including Kafue Gorge Upper	
	P3H1I1 (2035)			Baseline and existing irrigation (35021 ha)	(The World Bank, 2010)
	P3H1I2 (2035)			Baseline and short-term irrigation upgrade (39971 ha)	
	P3H1I3 (2035)			Baseline and long-term irrigation upgrade (65971 ha)	
	P3H2I3 (2035 full development)			Kafue Gorge Lower and Long-term irrigation upgrade	(Bhattarai et al., 2010; Spalding-Fetcher et al., 2014)

The approach quantified the vulnerabilities of the Lusaka city-scale water system and the city-regional scale water system of Lusaka and the Kafue Flats; which included the water dependent sectors hydropower and sugar agriculture. On a city-scale the greatest direct impacts to future resilience of the water supply for the city of Lusaka are socio-economic (i.e. population growth, percentage of non-revenue water, and the distribution between the urban and peri-urban population). However, changing climate conditions play a role in the uncertainty associated with future water supply, and in water dependent sectors at a city-regional scale when the impacts to the Kafue Flats sub-basin are considered. For the agriculture water dependent sector, increases in temperature will increase the risk. For the hydropower sector, decreases in precipitation will increase the risk. However, these risks cannot be considered in silos as the water-energy-food nexus is linked.

This Lusaka risk narrative has a specific focus on water, energy and food in the Kafue Flats region, Lusaka's main water source. To sustain water security for the population of Lusaka and the water dependent sectors of energy and food the risks and vulnerabilities for each sector need to be identified to allow for better informed decision making. The water risk narrative is partially hydrological; in that the physical water flow is of importance and are linked to the regional activities that impact the availability of water; and economic; which are dependent on production that derives from the Kafue Flats water resources such as hydropower generation and agricultural production. Risk definition was based on **Table 3**.

Table 3: Risk definition based on domestic and irrigation demand, and hydropower generation and reliability

Risk level	Average domestic water demand (incl. NRW)*	Average Irrigation demand	Total Hydropower generation	Hydropower reliability
Low risk	80%≤ of demand met	80%≤ of demand met	430 GWH/month≤ (based on average generation 1993-2012)	71.8%≤ (based on average generation 1960-1990)
Medium risk	75% of overall demand met	75% of overall demand met	408.5 GWH/month≤ (low risk -5%)	68.2%≤ (low risk -5%)
High Risk	65% of overall demand met*	65% of overall demand met	387 GWH/month≤ (low risk -10%)	64.6%≤ (low risk -10%)
Severe risk	<65% of overall demand met*	<65% of overall demand met	<387 GWH/month	<64.6%

Choices, **C**onsequences, **C**onnections and un**C**ertainties were used as a framework to evaluate the city-regional water system and its vulnerabilities. This framework identifies the city-regional **choices** regarding their water supply, the **consequences** to evaluate water security, the linkages and **connections** between different choices, and highlights the **uncertainties** that could affect resilience.

CHALLENGES AND CHANCES FOR RESILIENCE

The evaluation and the recommendations for resilience were cross-cutting. Measures for resilience in the evaluation considered the levels of socio-economic resilience, hazard resilience and socio-ecological resilience at a city and a city-regional scale. they are summarised below:

Socio-economic resilience: Integrating climate adaptation into national plans and policies to mainstream adaptation into the development context. The mandates of relevant institutions need to be strengthened to improve water management. Investing in and sharing of hydrological data to assess uncertainties generated by climate change is required. Investments should be made in the management and technology transfer.

Hazard resilience: The reduction of agriculture production, because of climate change, will create vulnerabilities for the Kafue Flats agriculture sector. A decrease in the allocated water, or its variability, will influence agricultural productivity. As most of Zambia's energy production is from hydropower, the streamflow volume and regime within the Kafue flats is important. Environmental changes in the Kafue flats e.g. siltation, also have detrimental impacts for the generation of hydropower.

Socio-ecological resilience: The city's water offtake from the Kafue Flats will be under pressure as population continues to grow. These pressures will be worsened if the volume of non-revenue water does not significantly decrease and infrastructure is not expanded. Migration to Lusaka and the Kafue Flats region, whether climate or socio-economically related will further stress the water resources given the competing uses.

BOTTOM-UP DECISION-SUPPORT

There are many advantages to the application of the decision-scaling framework; firstly, is that it is designed to engage with stakeholders and give guidance to decision-makers to manage risk; this helps to inform acceptable stakeholder-defined objectives and thresholds. Secondly the framework can rely on a wide range of sources for testing the hydrologic variations, thus including socio-economic changes, historical and modelled information and moving away from downscaled projections (Poff et al., 2015). Thirdly, the framework helps in identifying vulnerabilities early in the decision-making process, allowing for potential system trade-offs to be identified and addressed early on. Exploring the vulnerabilities of a system, based on multiple performance indicators, can minimize the decision consequences of an uncertain future, and promote informed decision-making processes facilitated by bottom-up discussion.

CONCLUSIONS AND RECOMMENDATIONS

The application of bottom-up adaptation decision-support is useful to inform decision-making for water security, despite changing climates, these measures will require innovative thinking and use of local knowledge (UNU-INWEH, 2013, p.16). The city-scale and city-regional scale (inclusive of the water-energy-food nexus) water systems of Lusaka and the Kafue flats are co-dependent and have varying spatial and temporal vulnerabilities to climate and socio-economic changes for a range of development scenarios. The choice of climate and socio-economic changes to consider in decision-support will have consequences, connections and uncertainties which should be addressed by water managers in collaboration with decision makers for water dependent sectors. Water security in Lusaka has chances for socio-economic, hazard and socio-ecological resilience respectively. A limitation to the research was the minimal experience in crop and energy modelling which simplified the city-regional system. The case study results were unique to the city of Lusaka, but the challenges and chances for resilience can be broadly applied in urban African context as there are common system complexities. Recommendations for further research include a study to identify and compare the trade-offs and vulnerabilities between different urban centres; and inclusion of water quality in the modelling process.

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ACRONYMS & GLOSSARY

CSAG	Climate Systems Analysis Group
DFID	Department for International Development
Eto	Potential Evapotranspiration
FCFA	Future Climates For Africa
FRACTAL	Future Resilience for African CiTies And Lands
GwH	gigawatt hours
ha	hectares
IPCC	Intergovernmental Panel on Climate Change
km^2	square kilometres
l/c/d	litres per capita per day
LCC	Lusaka City Council
LuWSI	Lusaka Water Security Initiative
LWSC	Lusaka Water and Sewerage Council
m^3/day	cubic metres per second
m^3/s	cubic metres per second
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
mm	millimetres
NERC	National Environmental Research Council
NWASCO	National Water And Sanitation Council
UN	United Nations
WEAP	Water Evaluation And Planning Tool
ZDSS	Zambezi Decision Support System

Adaptation: Adaptation to global warming refers to actions aimed at coping with climatic changes that cannot be avoided and at reducing their negative effects. Adaptation measures include the prevention, tolerance or sharing of losses, changes in land use or activities, changes of location and restoration. (Government of Zambia, 2010a)

Climate change: A change of climate, which is attributed directly or indirectly to human activities that alter the composition of the global atmosphere, and which is additional to natural variability, and observed over comparable periods of time. (Government of Zambia, 2010a)

Hydropower Generation: The power generated by reservoirs and hydropower nodes (Sieber and Purkey, 2011)

Hydropower reliability: The percent of the timesteps in which a reservoir's hydropower energy demand was fully satisfied. For example, if a reservoir has unmet hydropower energy demands in 18 months out of a 10-year scenario, the reliability would be (10 * 12 - 18) / (10 * 12) = 85% (Sieber and Purkey, 2011)

Integrated Water Resources Management: is a process that promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Government of Zambia, 2010b)

Non-revenue water: this is the difference between the treated water distributed and the water billed consists of both leakages, illegal connections, wastage and unbilled customers

Resilience: The ability of a system to adapt to climate change, whether by taking advantage of the opportunities, or by dealing with their consequences (Government of Zambia, 2010a)

Sub-basin: is a geographical area which naturally drains into a water resource and from which the water resource receives surface or ground flow which originates from rainfall. (Government of Zambia, 2010b)

Sustainability: Is development which meets the needs of current generations, without compromising the ability of the future generations to meet theirs. (Government of Zambia, 2010a)

Vulnerability: The degree of susceptibility to the negative effects of climate change. It is a function of the type, magnitude and frequency of climate events to which a system is exposed to (exposure) as well as sensitivity and capacity for adaptation (adaptive capacity). (Government of Zambia, 2010a)

Water Resources Management: includes planning for sustainable development of the water resource and providing for the implementation of any catchment management plan and national water resources strategy and plan; promoting the rational and optimal utilisation, protection, conservation and control of the water resource; and improving the access to sufficient quality, quantity and distribution of water for various uses. (Government of Zambia, 2010b)

Water Demand: The requirement at each demand site, before demand site losses, reuse and demand-side management savings are taken into account. (Sieber and Purkey, 2011)

Water security: Sustainably safeguarding access and supply of adequate quantities of water at an acceptable quality to sustain socio-economic development and well-being of humans and the ecosystem in a peaceful and politically stable environment UNU-IWEH 2013

ABSTRACT

Urban African water systems need to be managed for resilience to both climate and socio-economic changes, the research investigates a city-centric approach to identify vulnerabilities of water systems to climate and socio-economic changes. Decision-scaling, a bottom-up decision-support adaptive approach, was applied as a methodology to inform short to medium-term decision-support using a case study of the city of Lusaka, Zambia.

Decision-scaling framework identified the risks to the water system at a city and city-regional scale for both current and future scenarios. The framework uses stakeholder engagements, in the form of city learning labs, to define a conceptual model of the water system, using WEAP. The Lusaka water system was stressed for domestic city-scale demand and city-regional demands for the agriculture and energy sector. The research linked the “physical systems” of water with the “human systems” of knowledge and control; investigating where challenges and opportunities exist for resilience of the city of Lusaka as part of the Kafue Flats sub-basin.

Key words: urban water systems, decision-scaling, African water security, decision-support, resilient water

To those in the room…

embrace complexity and change

they are inevitable.

1.INTRODUCTION

1.1 Background to study

Water and its security are central to sustainability and development (UNU-INWEH, 2013). To properly address the challenge of water security, water managers and policy-makers need to identify vulnerabilities of water systems and the consequences thereof. Sustainably managed formalised water systems have less risk to their water security when they are resilient and less vulnerable to external stressors (UNU-INWEH, 2013). This research investigates adaptive decision support for city-regional water security and the resilience of urban African water systems to climate and socio-economic changes. Resilience can be defined as a social or ecological system's ability to retain its structure and manner of function while absorbing system disturbances; the system has the capacity to be adaptable when stressed or changed (Tyler and Moench, 2012; UNESCO, 2012). The growth of cities includes the development of formal and informal water resources; which are exposed to changing climates, environments, economies and demographics; some of which are unforeseen by decision makers (Eckart et al., 2011; Cooley et al., 2014). Identifying the risks to adaptation provides insights for informed decision-making.

The Department for International Development (DFID) and the National Environmental Research Council (NERC) currently have a project funded as one of the consortia of Future Climates for Africa (FCFA: www.futureclimateafrica.org) called Future Resilience for African CiTies And Lands (**FRACTAL: www.fractal.org.za**). FRACTAL focuses on several African cities and aims to advance scientific knowledge about climate responses to anthropogenic activity and improve inclusion of this knowledge into decision-making processes that contribute to resilient development. The proposed focus city of this research is the city of Lusaka, Zambia; investigating adaptation decision-support for its city-regional water system within the Kafue river Basin. The initial stages of the FRACTAL project in the city of Lusaka identified water supply and flooding as burning critical issues for the city. For this investigation, water supply was chosen as the focal critical issue as globally, rapid urbanisation and its implications are a growing concern for the future of water resource management (Closas, Schuring and Rodriguez, 2012).

1.2 Description of research problem

An integral part of human development, economic improvement, and environmental sustainability is water (UN, 2014). The task of conserving water resources is not one exclusive to private and public organisations. Governments and citizens worldwide have become aware of the negative impact that a lack of sufficient water, due to climate and socio-economic changes, will have on their economies and their populations (UN, 2014; UN-WWAP, 2016). African cities are amongst the places where rapid urbanisation is likely to have the greatest impacts for adaptation on both a spatial and temporal scale(UN, 2014; UN-WWAP, 2016). Water managers are accustomed to changing circumstances and adapting to them; however, climate and socio-economic changes have an additional layer of complexity which introduce their own uncertainties to decision making processes (Closas, Schuring and Rodriguez, 2012). Therefore, adaptation frameworks used for the evaluation and management of water resources should reflect the potential impacts that external factors have on a water system (Olmstead, 2014). The main problems that this research will investigate can be identified by three key aspects, namely:

1. **Water security for resilient urban livelihoods,**
2. **Adaptation in decision-making and decision-support under future uncertainty, and**
3. **Vulnerabilities of city-centric water systems to external stressors**

The main aspects of the research problem will be incorporated into the research question and addressed by the research aim. The sections in the research are summarised below.

Chapter 1 Introduction: background to the research, research aims, objectives and the assumptions

Chapter 2 Literature review: analysis of existing literature about water systems and their management and dependent sectors in an urban context, resilience and adaptation decision-support frameworks, the city of Lusaka, Zambia within the Kafue Flats sub-basin

Chapter 3 Methodology: description of the methodological approach and the decision-scaling

Chapter 4 Case Study results: identifying and quantifying city-centric risks and vulnerabilities for Lusaka's water system as a dependent of the Kafue Flats sub-basin

Chapter 5 Discussion: benefits of the application of bottom-up adaptive decision-support methods to identify urban system vulnerabilities and challenges and opportunities for resilience

Chapter 6 Conclusion and Recommendations: realization of the research objectives, limitations to the research and recommendations for further research

1.3 Research aim and objectives

African cities are in the process of significant social, economic and demographic transformation which are likely to have an influence on water resources (Petheram et al., 2014). An opportunity exists to initiate structured adaptation responses for water management, which will be affected by system changes (Muller, 2007). The goal of the research is to improve urban water decision making. Through a case study of the city of Lusaka, a co-dependent city of the Kafue River Basin, the proposed research **aim is to investigate a city-centric approach to adaptive decision-support, to better inform African urban water system resilience to climate and** socio-economic changes. **Table 1-1** summarises the objectives and associated research questions that are linked to the aim of the research.

Table 1-1: Objectives and associated research questions developed for the research aim

Objectives	Research questions
1. Explore city-centric water system and the climate and socio-economic sensitivities and uncertainties of the system at a city-regional scale.	1.1 What are the climate and socio-economic stressors to a city-regional water system? 1.2 How do city-regional sensitivities to change translate into city-centric impacts on a water system?
2. Quantify the vulnerabilities of African urban water security and its dependant sectors, due to external stressors, by developing a city-centric water resource model of the city of Lusaka reliant on the Kafue River Basin.	2.1 What are the dependent sectors of African urban water security? 2.2 How can the vulnerabilities of a water system, and its dependent sectors, be quantified to inform resilience?
3. Inform short to medium-term decision-making by evaluating the water system's vulnerabilities, using an adaptation framework for decision support.	3.1 How can vulnerable water systems be more resilient in the short to medium term? 3.2 What adaptation frameworks are used for water management decision support?

Answering this question using literature and a methodological approach has the potential to address ways in which urban water can be better managed in African cities, and how the available resources and their development can be more resilient to a range of future uncertainties.

1.4 Assumption statement

The assumptions made in this research are based on a limited time frame during which knowledge about the research topic could be acquired. The research is to be carried out within Zambia, Lusaka, thus the assumption is made that local policy and frameworks are effectively applied. Assumptions are based on an understanding of the overarching objectives for the FRACTAL project and that this study will be practical and useful in achieving these objectives. Assumptions include obtaining the necessary critical information, particularly with regards to key thresholds for decision making; and a baseline understanding of the current and future operations of the Lusaka and Kafue River water system. The research also assumes that there will be direct interaction with the relevant stakeholders from the city of Lusaka. The dissertation is based on modelling and data collection methods incorporated within the FRACTAL research project. The FRACTAL research is carried out in a team, the assumption is that contributions and inputs from the rest of the FRACTAL team may be used, with consent and acknowledgement thereof, to support the methodological approach to achieve the research objectives described in this proposal. The proposed time frame assumes the availability and accessibility of the necessary models and information to support these models and the technical ability to learn and apply these models.

2 LITERATURE REVIEW

This section focuses on sourced existing literature about the key aspects of the proposed research. Firstly, the section describes the search strategy used to source the literature; this includes a description of the search boundaries and the quality assessments used to source the literature. Secondly the sub-sections outline key findings in literature for each of the principal areas of focus of the research, namely; water systems and their management and dependent sectors in an urban context, resilience and adaptation decision-support frameworks, the city of Lusaka, Zambia within the Kafue Flats sub-basin; further literature included water institutional frameworks and policies. The literature searched aimed to answer the research questions outlined in the introduction that support the objectives and the research aim. Recommendations for further literature that will be incorporated in the final dissertation will be focused on the same topics as those outlined in this section.

2.1 Literature search strategy

Reducing uncertainties associated with water challenges needs enough knowledge. The literature search included both primary and secondary sources that reviewed the academic and organisational literature on the implementation of adaptation frameworks and modelling water resources, with a city-centric approach, to better inform planning and decision-making for African cities. The literature, considered five principal areas of focus that formed the broader search boundaries, namely: “water and urbanization”; “African cities”; “climate and socio-economic resilience”; “adaptation decision making” and “city-regional water systems”. The overlap in the available literature was filtered by combining the broader search boundaries in searches and filtering them by availability of resources (e.g. free and online).

The available texts and sources were quality checked to verify their reliability, relevance and information scope (Fisher and Reed, 2012). The chosen research goal was found to be current in literature, as African development and adaptation, water resource management and urban resilience have been contemporary issues since the beginning of the millennium and more so since the establishment of the Sustainable Development Goals.

The broader search boundaries reviewed literature for both a logical and a “snowball” (Fisher and Reed, 2012) search approach of available sources. Google scholar, the WEDC Knowledge Base, the Loughborough University library, NGOs (e.g. UNWater, WaterAid, IWA), Government organizations (e.g. Lusaka Water and Sewerage Company, Lusaka Water Security initiative, National Water Supply, and Sanitation Council) and specific journals (e.g. Journal of Hydrology, Environment and Urbanization, Climate and Development) were used as initial search sources to search combinations of the broader search terms. The number of results obtained from the search terms prompted either refining or expanding the search. Other searches included the related and recommended articles or the "see also" sections; as well as an author search on Mendeley for authors whose work appeared more than twice under a specific search term. The literature search results were sorted by relevance; quality assessments of the sourced literature looked at the following components:

- Skimming and search reading the available documents searching for keywords and phrases to verify whether they were relevant in the context that they were presented
- Citations, where applicable, were an indicator of how much of an impact the source or the author had on other potentially related work.
- The reputation of the journal/ publisher/ database from which the literature was sourced, and whether the journal or text was peer-reviewed as a quality check prior to publication
- Articles written within this millennium and limited to sources available online; as these could be updated more often, as oppose to books.
- Literature referenced/associated to organisations with specialisation in the water sector
- Abstracts and the arguments made by the authors, prior to reviewing the entire document
- Verifying if the text had practical or experimental evidence.

The search terms and search sources were based on those that would give a wide enough scope to perhaps find components that not initially considered but that were still relevant, while ensuring that the search was not too broad. Literature was stored in Mendeley using the broader search terms as a folder structure, this search process found 220 documents for review; of which 120 were flagged as having highly relevant information based on the abstract/introduction/executive summary. The literature included mostly scholarly journal articles, and private/government institutions' review reports and guidelines. Literature that was identified as the most relevant to the research aim and objectives was starred, and notes were made on the relevant chapters to read first. Although the research is focussed on African cities, the global context of urban water security and management also gave insight and comparisons of adaptation applications in decision making.

2.2 Research Gap

Our understanding of the drivers of African climate change and urbanization is improving, however, there exists relatively little work on the links between climate change risks and urban development (Calow et al., 2011; Jones et al., 2014). To inform future investment and development decisions, a better understanding of the impacts of climate change, variability on water, and its dependent energy and food supply systems, is required (UNESCO, 2012). Ensuring that policy and decision makers can respond to long-term impacts of climate and socio-economic changes is important in promoting development that is resilient. The practical application of the research is to create a holistic understanding of urban water decision-making, management and security, in an African context, and to investigating where challenges and opportunities exist for adaptation frameworks in decision-making (AMCOW, CDKN and GWP, 2012a; Closas, Schuring and Rodriguez, 2012). Identification of these challenges and opportunities gives a platform for developing resilient city-regional water systems.

2.3 Setting the scene of water systems

2.3.1 A picture of water management and security

Water is a finite resource which serves multiple uses and people, for which a reliable supply is essential for sustainable development (UN-Water, 2018a). One of the challenges to water security over the next few decades is how the social and ecological water sub-systems will be affected by climate change, urbanization and a decrease in the availability of the resource (Butler et al., 2017). Water resource management is dependent on two components, the first being the direct component of water supply and demand which considers all available water resources, how they are managed and how they can be best utilised to the communities (UN-WWAP, 2016). The second component of water resource management (including land use and the surrounding environments) is indirect; this includes environmental requirements, agriculture and urban development (Closas, Schuring and Rodriguez, 2012).

According to the UNU-INWEH (2013, p.1) a working definition of water security is; “the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability”. The scope of this research will focus on sufficient water supplies for domestic use and socio-economic development, specifically energy and agriculture. Use of the term “water security” as an umbrella term for the management of these water issues allows for a holistic approach to management, and solutions between the sectors (UNU-INWEH, 2013, p.3). the working definition of water security for this research is Water security: Sustainably safeguarding access and supply of adequate quantities of water at an acceptable quality to sustain socio-economic development and well-being of humans and the ecosystem in a peaceful and politically stable environment.

Water security is a complex and has co-dependent and connected challenges with other sectors making it central to achieving holistic security, sustainability and development (Chomba and Nkhata, 2016). Water makes a significant contribution to overall human security making a contribution to achieving an adequate level of health, food and healthy environments (UNU-INWEH, 2013, p.5). Changing demographics, increased urbanization, demand changes and changes to the hydrological cycle will all impact on the availability of water and its cycle; while sectoral competition of water dependent sectors will also put a strain on the resources (UNU-INWEH, 2013, p.6). Decisions made that affect the water sector are often made in broader policy frameworks and not exclusively by water managers (see process in **Figure 2-1**); making trade-offs and multi-sectoral coordination important considerations for decision-making

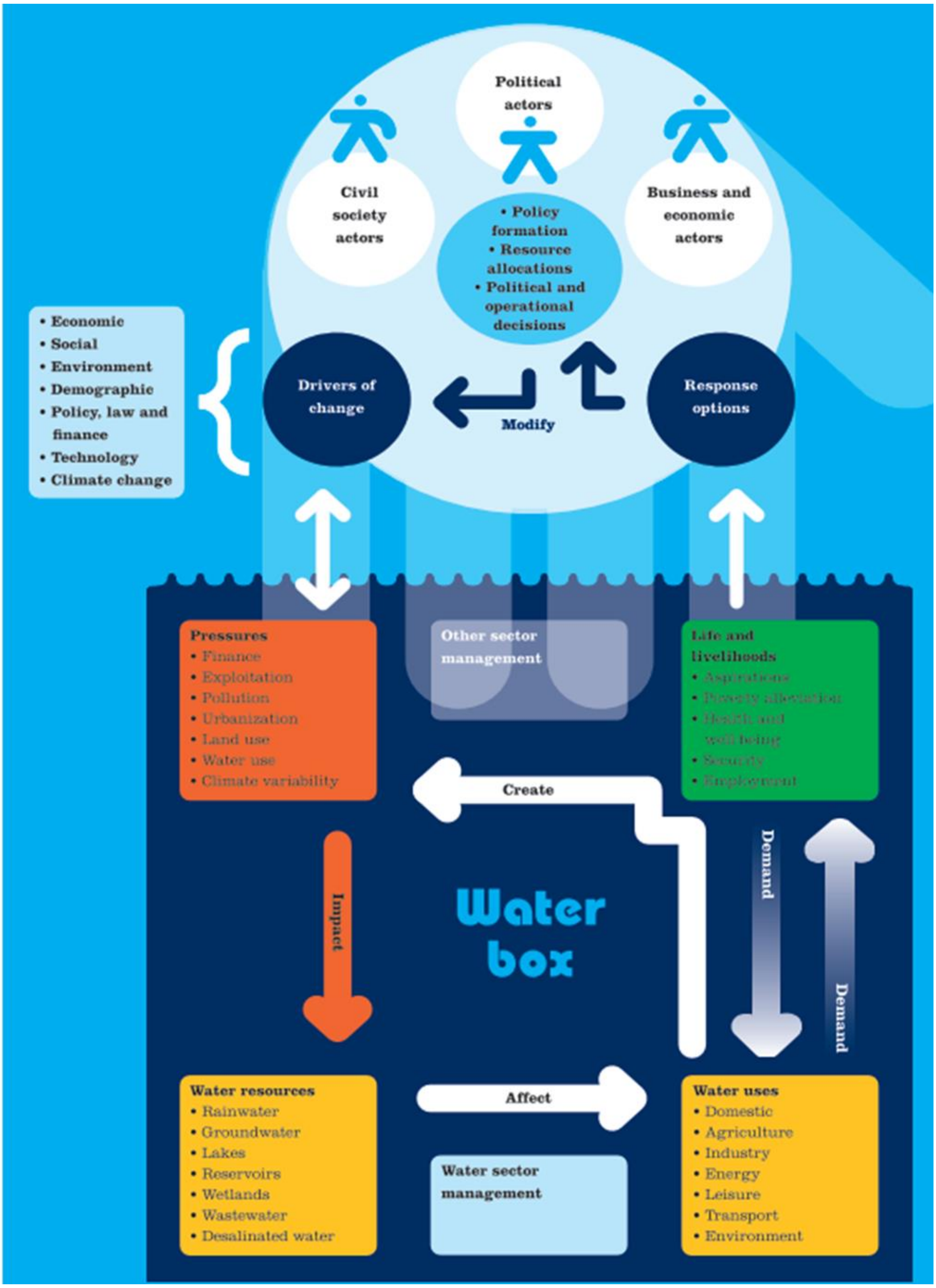

Figure 2-1: Decision making affecting water (UN-WWAP, 2009, p.5)

The water demands of different sectors will require cross-sectoral, coordinated decision making and policies to avoid competition for a limited resource (UNU-INWEH, 2013, p.6). Achieving water security is dependent on for whom, for what purpose, and at what service level the security is being achieved as security for some regions may be at the expense of security in others (UNU-INWEH, 2013, p.9). This highlights the importance of finding trade-offs for water security.

Ensuring water security at both an individual and urban scale requires recognition of safe drinking water as a basic human right and addressing the demand and supply concerns of the vulnerable (UNU-INWEH, 2013, p.11). Investment may be needed to ensure water security; however, these investments offer potential economic growth, human development and environmental sustainability in the long term and increased employment and education opportunities in the short term. Water security can be achieved if there is institutional support and capacity for change, and multi-layered models that can integrate the natural and social dimensions of water (UN-Water, 2013). Climate change will have vast impacts on the water cycle which, as a result, will affect water security as there will be higher hydrological variability.

2.3.2 Climate and socio-economic water drivers

The effects of climate change will be primarily felt through the water sector; as water availability becomes less predictable climate change mitigation and adaptation strategies seek to ensure the sustainability of the resource (Johannessen and Wamsler, 2017; UN-Water, 2018b). Climate change has been highlighted as one of the most important challenges of the 21st century which has resulted in a number of studies being conducted to focus on adaptation measures for responding to climate changes (Eckart et al., 2011; Grijsen et al., 2013). There exists an inconsistency of the quality and quantity of research and planning tools available in the African context to facilitate adaptation to system changes (Awadalla et al., 2012). According to Muller (2007) the quality of the necessary climatic and hydrological information to design new water management infrastructure is lacking; especially in the case of poorer countries who have limited information to support the planning, development and management of water (Kemp, Fairhurst and Tarryn, 2011; UN-Water, 2016).

In an urban environment, decision-makers' failure to address climate change impacts on water resources will create vulnerabilities for inhabitants (Calow et al., 2011; AMCOW, CDKN and GWP, 2012a). Muller (2007) describes some of the potential vulnerabilities as flood damage, water and electricity supply failure affecting the sustainability of urban communities, and financial costs that will render water related services unaffordable. In Africa, this is especially relevant as these are some issues already experienced in urban areas, and ways should be found in which the systems can have a greater adaptive capacity (UNESCO, 2012; Ray and Brown, 2015). The manifestation of climate change in the water cycle is complex because precipitation varies in the form of Mean Annual Precipitation (MAP), seasonal variation, inter-annual flow variability and precipitation intensity (García et al., 2014). To fully understand the climate risks for water availability for urban communities the capability should exist to predict average rainfall, streamflows, extreme flows, storms, and potential changes in groundwater yields.

In the context of sub-Saharan Africa the most likely and critical climate changes that will have an impact on surface water and river discharge are; increased precipitation (its intensity and frequency), potential evaporation, and vegetation and land use changes (Calow et al., 2011, p.5). the predicted higher temperatures in the region. Increased intensity of precipitation coupled with increased evaporative demands may result in land degradation, reduced recharge of groundwater and a decrease in the quantity of surface water resources available (Calow et al., 2011, p.5). In Africa, specifically sub-Saharan Africa the uncertainty regarding future precipitation results in uncertainty with regards to future river flows and whether they will increase or decrease; however these changes will be more dependent on precipitation that temperature changes (Calow et al., 2011, p.6).

According to the Intergovernmental Panel on Climate Change (IPCC), over the past century Africa has lacked sufficient observed data to identify significant precipitation trends (Niang et al., 2014, p. 1209). Countries in the Zambezi river basin are predicted to have increasing climate related surface water shortages, however, non-climatic factors, such as urbanization, population growth, increased reliance on irrigation and land use changes, are expected to have a stronger influence on the availability of water in the future (Niang et al., 2014, p. 1217). With increases seasonality to the surface water resources, there is expected to be a greater dependence on groundwater resources which will be less vulnerable to climate change (Calow et al., 2011, p.10).

The climate stressors for groundwater resources are uncertain, however this is critical as up to 80% of sub-Saharan African water supplies are thought to be groundwater dependent (Calow et al., 2011l, p.7). Similarly, to surface water resources, climate change impacts on groundwater will have climatic zone variability and will be strongly affected by non-climatic factors. In areas that receive more than 500mm of rainfall per year, it is expected that, assuming current day extraction rates from aquifers, sufficient recharge would remain even with decreases in rainfall (Niang et al., 2014, p. 1217).

According to Poff et al. (2015, p.1) “Securing the supply and equitable allocation of fresh water to support human well-being while sustaining healthy, functioning ecosystems is one of the grand environmental challenges of the twenty-first century, particularly considering accelerating stressors from climate change, population growth and economic development”. Socio-economic changes provide their own set of pressures on water systems that increase their vulnerability and sensitivity (AMCOW, CDKN and GWP, 2012b). The world’s population growth, over the next four decades, is expected to be absorbed into urban areas to accommodate for rural-urban migration (UN-Water, 2018c). To ensure the sustainable growth of cities, secure water systems will be essential (UN-Water, 2018c). The urban areas of low-income countries have the fastest population growth rate and they provide opportunities for integrated water use and management (UN-Water, 2018c). Although climate and socio-economic drivers can be independently identified separating the impacts of and responses to the two sets of drivers respectively is not straightforward (Calow et al., 2011). Finding how these drivers change within the urban context and how they affect water resources will help decision makers better manage the water sector.

The current efforts for long-term planning of water resource systems need a link between climate and societal change projections and system performances under various planning alternatives (Steinschneider et al. 2015). Climate changes are likely to significantly increase weather-related risks facing human settlements (Muller 2007). Changing parameters that are predicted to influence water resources and in turn seeing how this change in water resources affects other factors. However, it should be noted that it is not always possible to address all concerns raised during the identification of climate uncertainties (Groves et al. 2014). Water resources are susceptible to weather and climate changes occurring at multiple temporal scales. The three distinct identifiable weather scales are average annual conditions, seasonal variations, and individual extreme events (Groves et al. 2014). The relationship of these scales in addition to the unique conditions of a water resource will dictate how the resource is affected by weather and climate.

In contrast to climatic changes, socio-economic changes have an associated certainty (Calow et al., 2011, p.16). The African urban population is expected to grow by 320% between 2000 and 2050, with an expected increase in water demand (Calow et al., 2011, p.16). According to Calow (2011, p.16) because access water access in developing countries is related to the wealth distribution, issues around water (in)security are the result of struggles relating to access, control, institutional frameworks and poverty as oppose to the naturally available water resources. This is further exacerbated by the assumption that water supply infrastructure is functional and operative at all times (Calow et al., 2011, p.16). Access rather than availability remains one of the key determinants of water (in)security; **Table 2-1** from Calow (2011, p.17) outlines technology choices for water supply that are available and the potential associated climate risks. In Lusaka, some of these technology options are at risk (Beekman, 2016).

The effects of climate change will have on available water resources is more difficult to predict because several effects combine to equate available water resources (Muller 2007). For example, temperature changes affect evaporation which affects flows into rivers and seepage into underground aquifers, however simultaneous changes in precipitation intensity will affect runoff; this is without consideration for the land use changes, because of the temperature and precipitation changes, which also affect water availability.

Table 2-1: Technology choices for future water supply in Africa (adapted for water supply options in Lusaka, Zambia)

Technology	Climate risks	Impacts	Responses
Rainwater harvesting	There may be fewer rainy days, longer drought periods or more intense	More storage may be needed to bridge low rainfall periods. Danger of damage and contamination from flooding	Build in redundancy for potential reduced rainfall and longer dry seasons Ensure protection against flooding
Shallow family wells	More intense rainfall, longer dry season	Increased contamination of sources More likely that sources will fail	Should generally not be promoted in isolation as improved water supplies
Improved hand dug wells	More intense rainfall, longer dry season	Increased risk of contamination More likely that sources will fail	Hand dug wells should be tested at the peak of a normal dry season. They should be sited in productive parts of the aquifer and deep enough to intersect groundwater below 10 m There should be an emphasis on casing out shallow layers and runoff
Boreholes	Longer dry season – more intense rainfall	Higher demand in extended dry seasons may cause source failure, and in some cases depletion of water resource. High demand can lead to mechanical failure. Risk of supply contamination from very shallow layers during intense rainfall events	To improve reliability, ensure boreholes are sited in most productive part of aquifer. Also, important to improve maintenance of the hand- pumps – particularly within the dry season. Ensure shallow layers of groundwater source are cased out to prevent contamination
Large piped schemes from large dams and rivers	Increased demand in cities. Changes in runoff and sedimentation affect storage	Larger storage should be able to cope with climate fluctuations Significant increase in demand may lead to failure	Larger storage therefore more resilient but increasing demand and reliability issues are a concern. Consider conjunctive use, supply backup and designing for higher demand at outset

2.3.3 Managing water dependent sectors

Central to sustainable development of water dependent sectors is the water-energy-food nexus (UNU-INWEH, 2013; UN-Water, 2018a). **Figure 2-2** shows how water consumption is closely linked to food and energy production, therefore changes to water resources is likely to have impacts on the other two components of the nexus and vice versa (UNESCO, 2012; Cooley et al., 2014; Rasul and Sharma, 2015a; Rasul, 2016; UN-WWAP, 2016). The intrinsic linkages between these sectors require a sustainable approach to their security, resilience and management as the largest consumer of the world's freshwater is agriculture, and 90% of power generation globally is water intensive (AMCOW, CDKN and GWP, 2012b; UN-Water, 2018a).

The three sectors underpin several of the sustainable development goals, however energy and food's dependence on water, has meant that decision-makers in all three sectors are focussing on integrated water resource management as part of their policy to ensure secure water supply (UN-Water, 2018a).

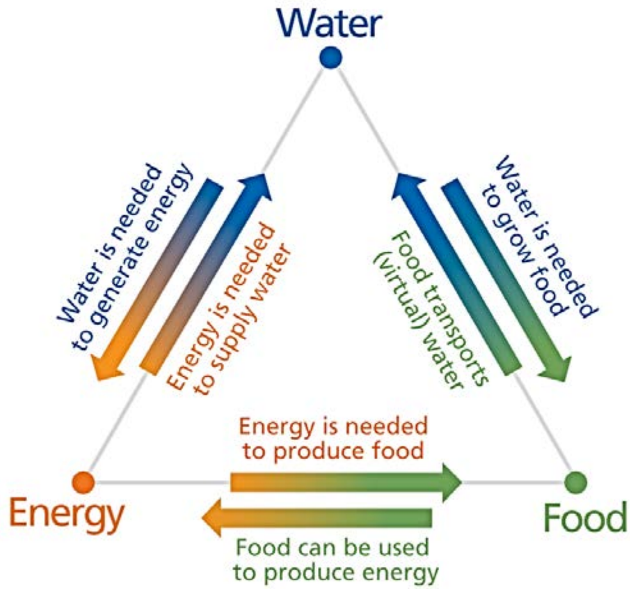

Figure 2-2: The Water-Energy-Food Nexus (UNU-INWEH, 2013, p.14; Rasul and Sharma, 2015b, p.7)

Water in Africa as an energy source (e.g. hydropower) has the potential to support economic growth and aid in climate change adaptation and mitigation (AMCOW, CDKN and GWP, 2012b). Africa has developed only one tenth of its hydropower potential, which is less than other world regions (AMCOW, CDKN and GWP, 2012b). potential future climate change impacts on hydropower could be influenced by long-term flow changes and droughts (AMCOW, CDKN and GWP, 2012b). Future plans for both rural and urban development include the development of substantial hydroelectric power (UNESCO, 2012). This development would provide a tool for enhancing activities in the Kafue River Basin as well as provide affordable electricity for uses such as irrigation and industry.

Agriculture is likely to remain the greatest consumer of water as the volume of agricultural demand continues to grow with population expansion (UN-Water, 2018a). As incomes in countries increase diets are moving away from starch-based to water intensive meat and dairy based diets (UN-Water, 2018a). Climate change will also impact agricultural demands as increasing temperatures and variable rainfalls reduce crop yields (AMCOW, CDKN and GWP, 2012b; UN-Water, 2018b). In sub-Saharan Africa, by 2080, land not suitable for agricultural use due to severe climate constraints may increase by 30 to 60 million hectares (UN-Water, 2018b). In 2012, irrigation accounted for less than 6% of the cultivated areas in sub-Saharan Africa as most agriculture was rain-fed, which has left potential to increase small scale irrigation to achieve food security as a viable option (AMCOW, CDKN and GWP, 2012b). In regions that are water scarce, protection measures are required to maintain agricultural production to ensure sustainable urban livelihoods (UN-Water, 2018a).

Governments and governance structures tend to have institutional structures whose mandates are along sectoral lines which often ignore the interdependence of the water, energy and food sectors and the potential consequences they can have on each other (UNU-INWEH, 2013, p.15). Holistically managing the security of the water, energy, food nexus takes into account inter-dependent decision making and supports a sustainability (UNU-INWEH, 2013, p.15). In a developing context, such as Africa, challenges such as urbanization and climate change place stress on water resources which develop into exponential consequences for the water, energy, and food sectors. By developing stronger links between water resources, and the sectors that are dependant in producing or using the resources, governments can promote better management. However, this should be paired with decision and policy making processes that are consistent and coherent (UNU-INWEH, 2013, p.16).

The demands for water, food and energy are expected to increase exponentially for people living in cities, which climate change is already threatening and will continue to threaten (Rasul and Sharma, 2015b, p.1). Future social progress and economic growth is constrained by the unsustainable consumption and production patterns of the nexus resources and there is an urgent need to address the security of water, food and energy (Rasul and Sharma, 2015b, p.2). Adaptation seeks to reduce vulnerability to climatic and non-climatic changes and is closely linked to water energy and food management for sustainable development. Addressing adaptation of the water-energy-food nexus evaluates the impacts outside of a sectoral focus, promoting synergy and co-benefits (Rasul and Sharma, 2015b, p.2).

The stresses on the water-energy-food nexus have been exacerbated by both climate and anthropogenic factors such as population growth and urbanization; making adaptation intrinsically linked to all three sectors (Rasul and Sharma, 2015b, p.3). A gap exists in the research of the role of the water-energy-food nexus in achieving sustainable adaptation which has led to an inefficient use of the resources and contradicting policies (Rasul and Sharma, 2015b, p.3). A strategy for resource management and adaptation to future challenges is to focus on the existing synergies and potential trade-offs of the water-energy-food nexus in a systemic way (Rasul and Sharma, 2015b, p.3).

The Kafue River basin is key in meeting the electricity needs of Zambia, more specifically Lusaka. ZESCO who is responsible for national power supply holds the largest water rights for water abstraction to generate hydropower (Pegasys and WWF, 2016). The current Kafue River hydro-electric system comprises the Itezhi-Tezhi reservoir, the Kafue Gorge reservoir and the Kafue Gorge Upper Power station, however, some hydroelectric potential in the Kafue river basin remains unexploited (Department of Energy and Water Development, 2007; Pegasys and WWF, 2016). The dams retain and store flows that exceed user demands and release the retained water during periods when the low flows are unable to meet user demands. They also can store high flows during flood periods to avoid flood damage. In addition to their ability to sustain urban settlements during periods of floods and droughts, dams can be used to generate electricity.

Currently the demand for electricity in the city of Lusaka is greater than the supply, although only 40.2% of households in the Lusaka province depend on electric energy (Pegasys and WWF, 2016). Capturing and controlling the river flows is one way of managing the impacts of climate variability on water resources (Muller, 2007). Hydrological flows are important in managing hydropower generation, but hydropower also changes the hydrology of rivers. The city of Lusaka consumes approximately 1800 GWh which is nearly 30% of Zambia’s electricity production; this is sourced from both the Kafue Gorge Upper hydropower plant and the Kariba Gorge (Pegasys and WWF, 2016).

Agriculture represent a large proportion of the water withdrawals within Zambia (approximately 73%), of which the majority is for sugar cane in the Kafue Flats (WWF, 2017). In addition to the sugar industry, private companies and a large concentration of cattle livestock also depend on the Kafue flats as their main source of water. Groves (2014) predicts that climate change warming will increase the irrigation requirements for both landscape and agriculture. For majority of the population in the flood prone Kafue Flats, agriculture is the main source of income. The agricultural sector of the Kafue basin provides both socio-economic and food security (WWF, 2017). The sector is highly dependent on rainfall, temperature, surface water and a labour force making it sensitive to both climatic and non-climatic changes. The Kafue Flats is one of the closest water resources for the agriculture that is transported to Lusaka for consumption.

A catchment scale model will help to identify the vulnerabilities of the agricultural sector to both climatic and non-climatic changes and how these may translate to city impacts (Chomba and Nkhata, 2016; Pegasys and WWF, 2016). The irrigable land area in the Kafue Flats has quadrupled between 1984 and 2015 (WWF, 2017).

The 7th National Development Plan (2017-2021) highlights agriculture and energy as growth sectors for Zambia; of which nearly 50% falls within the spatial hydrological boundaries of the Kafue Flats (Government of Zambia, 2017). As such, a nexus approach to adaptation is important for finding solutions that are applicable in the water, energy and food sector, to meet demands without compromising sustainability (Rasul and Sharma, 2015b, p.13).

2.4 Water in cities

City solutions often need to be sought at a local, city, national or regional scale because city problems can be caused by non-city-scale phenomena (Arrighi et al., 2016). Decision support based on a city-regional water system can support adaptation on a city-centric approach by promoting integrated approaches that coordinate between different sectors and at different spatial scales (i.e. local, national and regional).

Water resource management and adaptation are required to build urban resilience to climate and socio-economic changes (Muller, 2007, p.111). In the urban context, failure to address the adverse impacts of climate change on water resources could result in flood damage, water supply failures, and financial costs that will make water resources and services unaffordable (Muller, 2007, p.111). The World Bank (2012, p.23) defines Integrated urban water management (IUWM) as a way to adopt a holistic approach to dealing with the urban water cycle so that efficient and flexible systems can be developed. Integrated urban water management changes from the traditional approach of urban water management to an urban-water relationship (Closas, Schuring and Rodriguez, 2012, p.4).

The scope of this research will only focus on water supply, however IUWM includes sanitation wastewater, stormwater and solid waste management, which all affect urban water management. A fundamental part of IUWM is how cities are both dependent and impact their regional watersheds, for which ensuring water security for a city will require planning measures to be implemented at a watershed level to safeguard the supply of upstream and downstream users (Closas, Schuring and Rodriguez, 2012, p.4). In addition, socio-economic factors such as land use change and increased demand can also alter the availability of water and make the city supply system more vulnerable.

How climate change may affect the design, location and timing of African infrastructure in the short to medium term is unknown (Awadalla et al., 2012). To inform future investment and development decisions a better comprehension is required of the impacts of climate on infrastructure development and the planning approach for climate uncertainty and vulnerability. Several approaches exist for managing climate change uncertainty in water resource management, of which many are not mutually exclusive.

Traditional planning approaches assume regarding stationarity when planning for hydrologic conditions (Groves et al. 2014). Managing the impacts that variable climates will have on human activity, by building resilience, forms part of the daily activities of water managers; be it with regards to planning or optimization (Muller 2007). According to The World Bank study on the Future of Water in African Cities (The World Bank, 2012) the city of Lusaka (LUN) has a relatively high institutional and economic capacity city that is facing high water-related challenges (see **Figure 2-3**). Sub-Saharan Africa has the lowest urban concentration but is expected to have the highest annual growth rates , with the urban population expected to triple by 2045 (Closas, Schuring and Rodriguez, 2012, p.1).

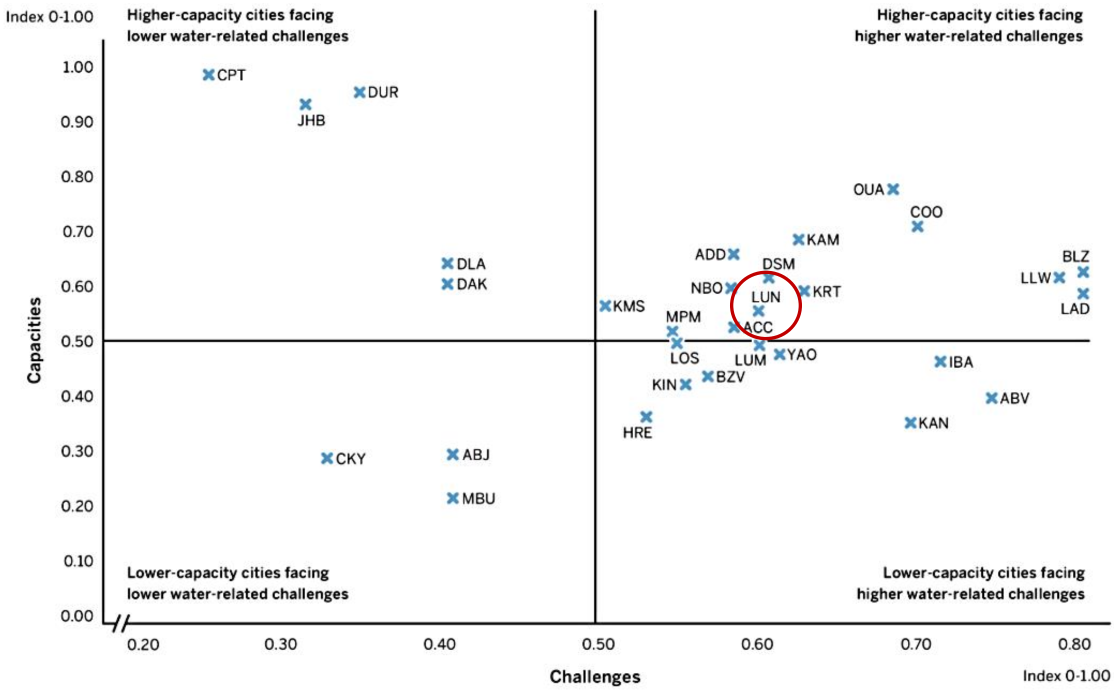

Figure 2-3: Urban water management challenges versus institutional and economic capacities (The World Bank, 2012, p.43)

"Water-related challenges dimension, indicators were selected for the following variables: urbanization challenges, solid waste management, water supply services, sanitation services, flood hazards, and water resources availability. For the institutional and economic capacities dimension, indicators were selected for the following variables: country policies and institution, economic strength, water-related institutions, and water utility governance." (The World Bank, 2012, p.43)

In Lusaka, Zambia the mandate to create a water secure and prosperous city falls to the Lusaka Water Security Initiative (LuWSI). LuWSI's water security action areas are preventing groundwater pollution and ensuring that it's exploited sustainably, maintain the health of the Kafue River, manage urban flood risks, and provide access to water and sanitation; these are based on the main threats to the city's water security (NWASCO and LuWSI, 2018). They aim to achieve these actions by delivering relevant projects that mobilise resources and actors, strengthening collaboration, and improving the information base related to water security to inspire change and create awareness

A large amount of the world's most rapidly growing cities are in Africa where there tends to be a limited capacity for decision-makers to plan the urban expansion and the resultant impact on water demand and supply (AMCOW, CDKN and GWP, 2012b; UN-Water, 2018a). The sub-systems of a city include the physical and natural environment that are lived and operated in, the connections of knowledge and behaviour between people, institutions and organizations, and the laws, cultures and norms (Tyler & Moench, 2012). The integration of these sub-systems promotes mutually supportive decision making that strengthens cities' systems and can manage risks; however, the interdependency of the sub-systems make a city vulnerable when one of the systems fails (Arrighi et al., 2016). Cities are complex systems in the context of future urban water resilience to climate and socio-economic changes, as a result, their vulnerabilities to variability in system stressors, of which climate change is only one, cannot be analysed in isolation. The population growth rates in Africa, specifically in urban areas, is significant. With the population of Africans living urban areas projected to grow to 50% in 2030 from 36% in 2010 (The World Bank, 2015). The challenges and opportunities associated with urbanization need to be considered in conjunction with climate change mitigation and adaptation efforts (Closas, Schuring and Rodriguez, 2012).

2.5 Unpacking resilience and adaptation

There has been increased research into resilience and adaptations in the water management approach, but use of these concepts in practice has not been as evident (Butler et al., 2017). There has been a rise in the use of the term resilience in reference to global environmental changes. Water systems are said to be resilient when they can cope with variability and have the capacity to return to their original form after a stress is applied to the system (AMCOW, CDKN and GWP, 2012b; Hepworth, 2014; Chmutina et al., 2016). The concept of resilience is open to multiple interpretations because it has origins in multiple disciplines; but has usually been applied to disciplines linked to sustainable development and climate change adaptation (Johannessen and Wamsler, 2017). Several arguments have been made for the need to define resilience or define what it looks like within a system (Walker et al., 2004; Smith, 2012; Chmutina et al., 2016; Butler et al., 2017; Johannessen and Wamsler, 2017).

According to Smith (2012), a common understanding of resilience within the water sector refers to the ability of a system to deliver a service regardless of disruptive impacts on the system. Walker et al. (2004, p.2) define resilience as “capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks”; this definition is similar to that by Folke et al. (2010). Resilience can also be considered as the measure of a system's ability to perform when the systems is unable to meet a specified level of service because its design conditions are subjected to unexpected threats (Butler et al., 2017, p. 65). All these definitions refer to resilience as a system's performance during its design life and the ability to reduce system failures when subject to changing conditions and when a specific level of service is not met.

An alternative definition of resilience has associated the concept with adaptability and adaptive capacity; by seeing a resilient system as one that absorbs disruptions and rearranges itself to better function; while accommodation the disruptions and maintaining its fundamental characteristics (Walker et al., 2004). This is contrary to the previous definition in that a resilient system is defined as one that can adopt a suitable new form instead of returning to its original form. The concept of “specified resilience” is important to consider in this study; defined by Folke et al. (2010, p.3) as; “The resilience “of what, to what”; resilience of some particular part of a system, related to a particular control variable, to one or more identified kinds of shocks”.

Although there is the risk of a system losing resilience to other disturbances if some parts of the system only have increased resilience to a specific set of disturbances; the scope of the study does not allow for coping with uncertainty in all ways. For this study, the definition of resilience that will be adopted will be based on the work by Johannessen and Wamsler (2017). Three levels of resilience to the urban water system will be considered namely; resilience that relates to socio-economic stressors (this includes institutional structures), external hazard resilience (this includes the patterns and extents of climate change related impacts) and socio-ecological resilience (this includes resource extraction by water service providers) (Johannessen and Wamsler, 2017) (see **Figure 2-4**).

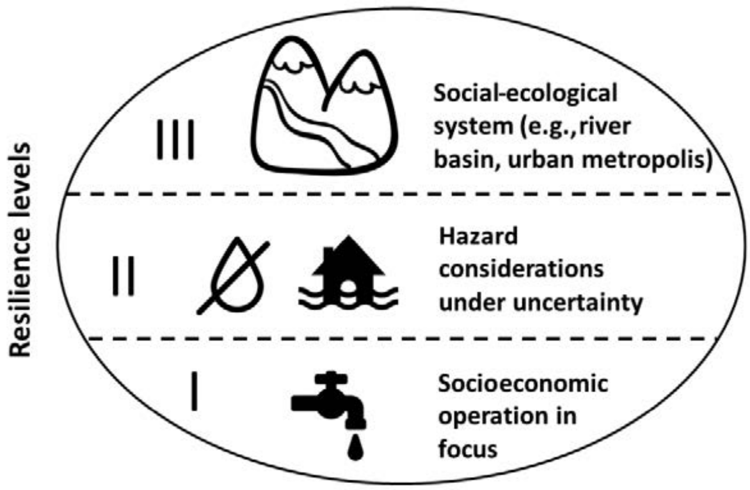

Figure 2-4: Three levels of perceived resilience (Johannessen and Wamsler, 2017, p.7)

The adaptive capacity of a water system are the characteristics that allow it to cope with variability; these include policies, support frameworks and assets (AMCOW, CDKN and GWP, 2012b). Calow et al. (2011, p. 56) and Folke et al. (2010, p.3) define adaptability as an adjustment in a system to a changing environment, stimuli or their effects such that the system moderates negative impacts. When actors within a system have the capacity to influence the system’s resilience, the system has a high level of adaptability (Walker et al., 2004; Butler et al., 2017). Adaptation differs from IWRM in that it is predominantly future orientated and deals with a time scale beyond the 10-year horizon, this is reflected in the uncertainties that adaptation approaches take into account (Ludwig, van Slobbe and Cofino, 2014). Adaptation activities; also referred to as 'no/low regret activities'; adapt systems to potential changes in both climate and socio-economic conditions and are designed for a range of future uncertainties as oppose to a more likely future (AMCOW, CDKN and GWP, 2012b). In recent years, interest in climate adaptation has increased and both adaptive capacity and vulnerability have become concepts required to understand adaptation (Rasul and Sharma, 2015b, p.4).

This research will focus on vulnerability as a system state, which is the context in which adaptation takes place. Adaptive capacity, is similar to resilience in that it is a system's ability or potential to reduce negative impacts by successfully responding to variability, specifically climate changes (Rasul and Sharma, 2015b, p.4). Applying adaptation that focusses on system vulnerabilities expands the adaptation from climate change impact responses to broader resilience that addresses the causes of the vulnerabilities as oppose to only responding to the system's symptoms (Rasul and Sharma, 2015b, p.4). This is the more modern application of adaptation approaches; how these applications have evolved is detailed in **Table 2-2.** In the current decade, adaptation is focussed on sustainable development, focussing on cross-sectoral and transboundary approaches.

Table 2-2: Evolving approaches to adaptation (Rasul and Sharma, 2015b, p.5; adapted from Calow et al., 2011).

Feature	1990s	2000s	2010s
Overall objective	Reducing climate risks and impacts	Reducing climate risks and uncertainties	Reducing climate risks and impacts with socioeconomic improvements
			Mainstreaming climate change adaptation into development
Scope	Sector-based approach, location specific	Sector-based approach, but adaptation mainstreamed into sectoral planning	Trans-sector and transboundary approaches started
Focus of activities	Protective: coping strategies, protection of those most vulnerable to climate risks and with low levels of adaptive capacity	Preventive: coping strategies, prevention of damaging strategies arising from risks to climate- sensitive livelihoods	Transformative: building adaptive capacity, transforming social relations to combat discrimination and underlying social and political vulnerability
Activities	Activities seek to address impacts exclusively associated with climate change: provision of social services; social transfers (food/ cash), including safety nets	Managing climate risks: activities seek to incorporate climate-related information into decision-making	Building response capacities: activities seek to build robust systems for problem solving
			Addressing the drivers of vulnerability: activities seek to reduce poverty and other non-climatic stressors that make people vulnerable

According to the World Bank global adaptation costs from 2010-2050 will annually range from US$70 billion to 100 billion with water supply being one of the sectors requiring the bulk of the investment and 80% of the total required funding being for urban areas (UN-WWAP, 2015, p.47). Constraints to the development of adaptation actions include climate change impacts, data scarcity, socio-economic and climate models with poor capacity to make predictions and inadequate decision support frameworks (UN-WWAP, 2015). Adaptation measures are targeted actions developed to cope with anticipated or actual threats that would impact a system, that cannot be mitigated (Butler et al., 2017). Integrating adaptation as a measure for decision support can better inform water management and help to develop systems that have a higher level of resilience, especially to climate and socio-economic changes.

The adaptation planning and implementation process are being facilitated by a number of approaches such as vulnerability assessments and scenario-based planning but the most effective form of adaptation remains climate resilient development (Calow et al., 2011). There is ongoing debate around the differentiation of adaptation and 'normal' development as adaptation efforts tend to mirror sustainable development a continuum (see **Figure 2-5**) exists for its application. In the water sector adaptation measures include both supply and demand measures that require either institutional or technical implementation. Supply side measures tend to be more often implemented in nation adaptation plans (Calow et al., 2011). The two ends of the adaptation continuum show the two distinct perspectives of the adaptation approach, but in practice the interventions applied often fall somewhere in between the two extremes, addressing the full spectrum of challenges (Rasul and Sharma, 2015b, p.5)

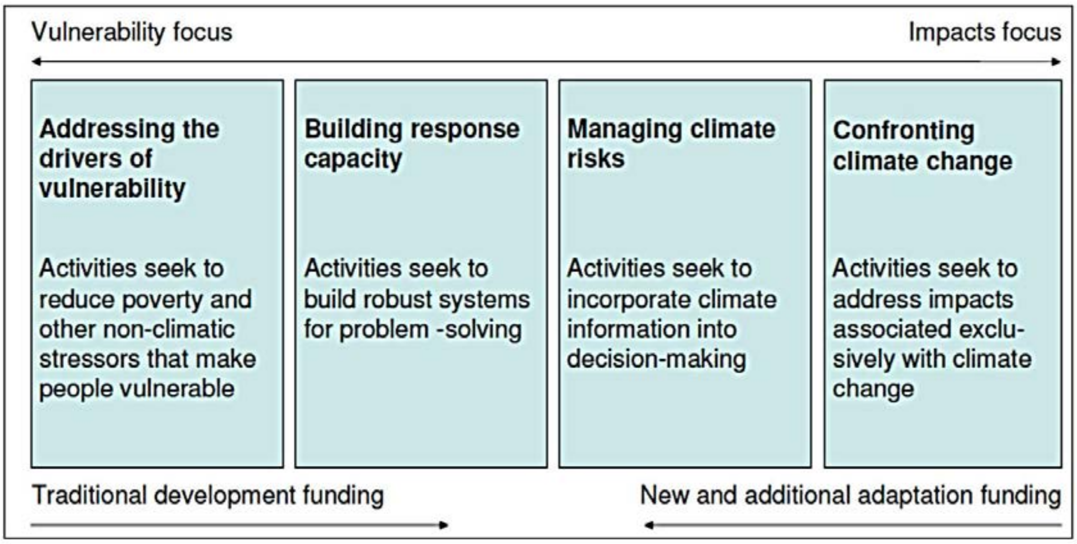

Figure 2-5: The adaptation continuum (Calow et al., 2011, p.20).

The United Nations through the Sustainable development goals (SDGs) aim to address issues relating to water resources and their management (UN General Assembly, 2015). Of the 17 goals, there are three that are highly relevant in the context of this research; namely:

i. SDG 6: Clean water and sanitation
ii. SDG 11: Sustainable cities and communities
iii. SDG 13: Climate action

If adaptation and resilience measures are to be effective they will need to go beyond considering these goals in silos.

2.6 Adaptation approaches

Planning tools used for the evaluation and management of water resources should reflect the potential impacts of climate change. This is in addition to the planning frameworks adequately addressing the uncertainty that climate change introduces (Groves et al., 2014; Ludwig, van Slobbe and Cofino, 2014). An opportunity exists to initiate structured adaptation responses for water management, which will be affected by climate change (Muller, 2007; GWP-Southern Africa, 2011). In developing societies, such as African cities, it has been proposed that alternative and more collaborative approaches to knowledge production and decision-making be adopted (Polk, 2015; Arrighi et al., 2016).

In African cities, co-exploration has been proposed as a collaborative approach that encourages climate scientists, civil society, businesses and NGOs to work together to understand and design the inclusion of climate information in urban decision making (Polk, 2015; Steynor et al., 2016). The co-exploration model shifts away from traditional approaches where knowledge for users is created by experts; research is undertaken with, instead of for, the society under study (Kemp, Fairhurst and Tarryn, 2011; Arrighi et al., 2016). Through inclusion of alternative approaches co-exploration of knowledge creates value in stakeholder engagements and an improved understanding of the resilience of systems in cities (Haasnoot et al., 2013; Arrighi et al., 2016; Kwakkel, Haasnoot and Walker, 2016).

The design and operation of future water systems has an associated deep uncertainty that will limit the acceptable performance of the systems (Groves et al., 2014; Ludwig, van Slobbe and Cofino, 2014). The current efforts for long-term planning of water resource systems require a link between climate and societal change projections and system performances under a number of planning alternatives (Steinschneider, Mearns and Brown, 2015). Adaptation approaches to system impact assessments can be generally characterised as ‘top-down’ or ‘bottom-up’ (see **Figure 2-6**), the methods are climate analysis-based and vulnerability analysis-based respectively (Brown, 2011; García et al., 2014; Ludwig, van Slobbe and Cofino, 2014; Ray and Brown, 2015). The top-down approach used downscaled Global Climate Models (GCM) projections for a climate change impact assessment whereas bottom-up approach assesses the climate related risk and vulnerabilities associated with a project (Calow et al., 2011). Traditionally, the top-down approach used GCM projections for a climate change impact assessment. However, according to Brown (2012, p.3) the bottom-up vulnerability based analysis has “changed the question we are attempting to answer from ‘what will the future climate be?’ which is very difficult with an infinite number of possibilities, to ‘‘is the climate that favours action A more or less likely than the climate that favours action B?’’.

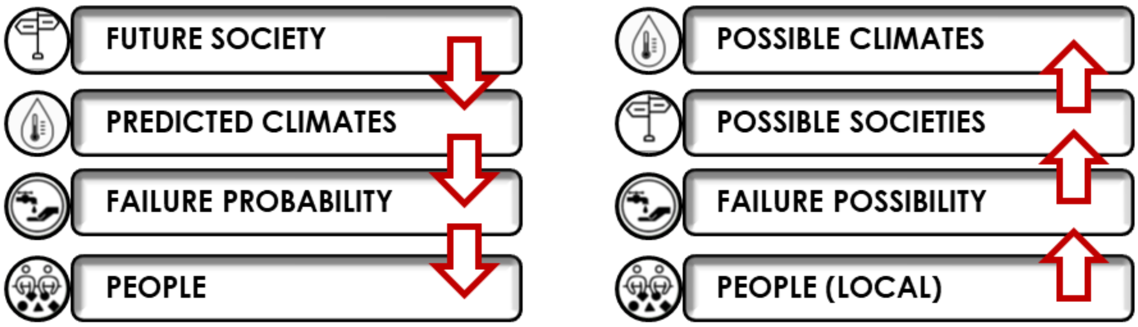

Figure 2-6: Simplified steps for top-down (left) and bottom-up (right) adaptation approaches

Ludwig et al. (2014) argue that both approaches are not suitable to be integrated into water management on the basis that the top-down approach complicates the decision-making process with its propagated uncertainties and the bottom-up approach does not develop technical solutions as its focus is on socio-economic vulnerabilities. However, the purpose of this research is not to find technical solution but to find ways in which those solutions can be better informed using an adaptation approach to decision-making. Top-down frameworks were developed to understand the long-term impacts of climate change whereas bottom-up frameworks were designed to focus on stakeholder involvement in the adaptation (Calow et al., 2011, p.27).

2.6.1 Top-down adaptation approaches

A top-down climate analysis makes reference to GCMs being used as a starting point (Brown, 2011; Butler et al., 2017) or looking at biophysical impacts on a large scale (AMCOW, CDKN and GWP, 2012b; Ludwig, van Slobbe and Cofino, 2014). The approach estimates for future regional climatic conditions for a variety of possible global economic and social trends, using GCMs, a range of scenarios and different impact models (Ludwig, van Slobbe and Cofino, 2014, Ray and Brown, 2015). The GCMs are projected on large grid sizes (250-600 km) which are then downscaled to be used in impact assessments. The process of down-scaling involves statistical methods or higher resolution models (Brown, 2011). Using a small sample of the projected GCMs decision-makers estimate future climate.

Limitations exist in top-down approaches, as the forecasts, although potentially informative, have uncertainties and unknown reliability that can often be propagated within the modelling (Brown, 2011, Ludwig, van Slobbe and Cofino, 2014). Assessing the projection reliabilities could potentially pose difficulties because the actual climate outcomes are uncertain. Top-down approaches often evaluate or test systems using only a small number of future scenarios. The uncertainty majorly lies in the projections being based on current understandings of climate responses to increasing greenhouse gas emissions (Brown, 2011). Although top-down approaches produce results with high uncertainties their aim is to reduce or improve quantification of uncertainties as an expert-dominated approach (Ludwig, van Slobbe and Cofino, 2014). Owing to the differences between climate models, planning for a specific model might contradict another therefore the analysis may not uncover all the possible climate impacts based on the limited range of GCM projections. According to García et al. (2014) time and resources can be disproportionately assigned to application of top-down approaches. This is in detriment of non-climate related analysis that could prove more important on shorter time horizons.

Climate projections are continuously being updated by the scientific community and, although useful, offer their own set of uncertainties. The primary uncertainty associated with a top-down approach that makes use of climate projections is that the approach does not allow for sampling from a full range of climate futures which may result in sampling from an incorrect range altogether (Ray and Brown, 2015). Downscaling global climate projections is associated with a number of uncertainties including (CDM, 2011):

- **Emission scenarios**: although these are viewed as the best representation of potential futures by the IPCC however there are uncertainties associated with future Green House Gas emissions
- **Data limitations**: the general circulation models (GCMs) are calibrated with historical datasets from developed countries which makes them unreliable to use in developing countries. However, it should be noted that GCMs are not the only source of climate information for top-down scenario-led approaches (Ray and Brown, 2015).
- **Scientific understanding**: there exist many questions regarding the Earth’s response to warming climate which the models do not consider.

In addition to the uncertainties of climate change projections, projections of non-climatic factors are also uncertain (Ray and Brown, 2015). Although useful, top-down approaches have large, irreducible uncertainties and tend to poorly represent climatic variability such as storm intensity-duration-frequencies that water resource professionals require to manage water resources (Poff et al., 2015). Because this approach is scenario-led, it tends to select a small subset of all possible futures. Top-down methods have a tendency to not provide the necessary insights for water resource planning decision-makers (Ray and Brown, 2015).

2.6.2 Bottom-up adaptation approaches

Bottom-up approaches focus on the factors that make a system vulnerable to current and future risks (AMCOW, CDKN and GWP, 2012b). There is a need for useful climate change information for decision-makers, for which bottom-up approaches are progressively more used as they focus on increasing a system's resilience when accounting for uncertainties and impacts (Brown, 2011; Butler et al., 2017). Several bottom-up approaches exist, but in general all the approaches begin with a stakeholder engagement and assessment of socio-economic systems. A system is characterized and its response to climate variation identified, based on a sensitivity analysis (Brown, 2011; CDM, 2011). In the final stages of bottom-up approaches the climate change vulnerabilities of the systems are identified and management prospects are established.

Bottom-up approaches do rely on top-down information (e.g. GCMs) to inform the likelihood of future climate conditions, without which the approach lacks a basis on which to select the range of vulnerability of the system (García et al., 2014; Butler et al., 2017). Collaborative bottom-up approaches are needed to develop sustainable management actions that are efficient, socially acceptable and meet the users' needs. According to Ludwig et al. (2014) the bottom-up approach has not often been applied to larger scales areas or urban areas but is useful in issue-driven cases where an uncertain future has been accepted and the focus is on the enhancement of the system's adaptive capacity.

The study by Ray and Brown (2015, p.13) promotes the use of "Ex Post Scenario Definition" as oppose to a scenario-led approach. This process of scenario definition allows for climate and other relevant data to be varied to find the vulnerabilities of the water resources system's performance; scenarios are then expanded based on the vulnerabilities that present themselves. The advantage of this approach is that it withholds the use of projections until the final stages of the modelling process this means that the climate change uncertainties do not feature in the analysis until the assigning of probabilities. The aim of adopting bottom-up approaches is to determine adaptation solutions, that support the decision making process and are insensitive to uncertainty (Daron, 2015).

2.6.3 Decision-support frameworks

To deal with the complexity of today's water problems, for which water managers need to make decisions, decision support frameworks create a shift from linear decision-making and highlight risks as a way of dealing with uncertainty (Hadka et al., 2015; Forni et al., 2016; Taylor et al., 2017). However, there is a limited application of these frameworks within an urban context (Taylor et al., 2017). Decision-support frameworks tend to be participatory and iterative and produce a range of learning outcomes which do need further investigation prior to a decision being made. Support methods (García et al., 2014; Ray and Brown, 2015; Maier et al., 2016) use formal approaches to analyse how a decision can be made between options. Taylor et al. (2017) outline the following decision-support methods:

- **Robust Decision Making (RDM):** usually used in water-related decision making where climate is a risk to the decision-making process
- **Structured Decision Making:** applications to climate change adaptation are rare but has been applied to natural resource management
- **Back casting:** application to date has mostly focussed on mitigation and has not often been used to analyse adaptation, although its vision-orientation makes it applicable
- **Analytic Hierarchy Process (AHP):** uses pairwise comparisons of criteria and options to incorporates different stakeholder views, value is mostly in the participatory discussions
- **Decision- Scaling**: handles poorly characterized uncertainties and incorporates alternative future visions, relating “bottom-up” vulnerability assessments with “top-down” climate information

For the purpose of this research; the literature review was limited to Robust Decision Making (Global Water Partnership (GWP), 2009; Lempert and Kalra, 2011; Matrosov, Woods and Harou, 2013; Ludwig, van Slobbe and Cofino, 2014; Bhave et al., 2016; Forni et al., 2016; Kwakkel, Haasnoot and Walker, 2016) (see **Appendix B**) and Decision-scaling (Management, Making and Scaling, n.d.; Brown, 2011; Brown et al., 2012; García et al., 2014; Mathews, Jeuken and Mendoza, 2015; Poff et al., 2015; Steinschneider, Mearns and Brown, 2015) (see the following section) as they both deal with unknown probabilities such as in the water sector and are similar in their application (Taylor et al., 2017). The main difference being that RDM tests the interdependencies of a given set of scenarios and options; while Decision-Scaling assess the plausibility of different scenarios to exclude those less likely.

2.6.4 Decision-scaling

Decision scaling (also known as Climate Informed Decision Analysis) integrates existing methods for climate risk assessment and robust decision analysis within a simplified framework for risk management by using a decision framework to reveal the scaling of system information that is needed to inform the decision (Brown et al., 2012; Ray and Brown, 2015). The process is robustness-based and uses stress test to identify system vulnerabilities. In Decision-Scaling, processed GCM projections can be geared towards identified critical climate conditions (Brown, 2011). Where GCM projections cannot be used, due to uncertainty, the decision-scaling method makes known the sensitivities of a specific planning decision to climate. Brown et al. (2011) simply explains the process as identifying the climate changes that would result in problems and then identifying how likely those climate changes are based on model projections. The process is designed to make climate information relevant and useful for real decision making and risk assessment.

The approach still makes use of climate information, which is still useful for certain analyses to inform the likelihoods of distinct types of climate change. There are three main steps to the Decision-Scaling process (Brown, 2011; Brown et al., 2012). The first step is identifying decision thresholds and concerns by producing specifications of the preferable decisions for a range of climate conditions. This step includes characterising the system in terms of the model and setting thresholds on tolerable conditions based on stakeholder engagement. It involves the characterization of objectives and performance indicators through discussion. This step addresses the gaps that hinder the integration of science and decision making, namely communication (Jones et al., 2014).

Secondly the response function –which is the representation of a specific system and its response to changing conditions- needs to be modelled to initially estimate those that cause risk. The response function represents the results of the established model in a form that, where applicable, links the climate and non-climate variables (or stressors), and determined performance indicators. Through the systematic variation of stressors, the response function is “stress tested” and diagnoses how the varied stressors affect the system. Lastly the method includes evaluating the system vulnerabilities and estimating the probability of changing conditions and identifying development futures that favour a decision over another.

Examples of the application of the decision-scaling approach exist for the Niger Basin (Brown, 2010) and for the Upper Great lakes in North America (Brown et al. 2011). Decision-scaling features prominently in the decision-tree framework for its efficacy and scientifically defensible approach (Ray and Brown, 2015). Further literature looked at case study applications of decision-scaling, specifically in a water context (examples include: CDM, 2011; Weaver et al., 2013; Mathews, Jeuken and Mendoza, 2015; Steinschneider, Mearns and Brown, 2015; Kwakkel, Walker and Haasnoot, 2016; Yang et al., 2016; Shortridge, Guikema and Zaitchik, 2017).

2.7 Water in Lusaka and the Kafue Flats, Zambia

Water is a valuable natural resource in Zambia (Casarotto, 2013). Zambia has vast ground and surface water resources as well as renewable hydro energy sources for which changes in climate will affect the utilisation and exploitation. Both the agriculture and hydropower sector are recognized as priority sectors by the Zambian government (Casarotto, 2013). The population of Lusaka has nearly tripled since the independence era and is one of Africa’s fastest growing cities (Pegasys and WWF, 2016). Lusaka’s current water demand is exceeding what the LWSC and available water resources are formally able to supply (Beekman 2016). Domestic water use for Lusaka is abstracted from surface water of the Kafue River, a major tributary of the Zambezi River Basin. This demand competes with that for hydropower generation, but flows contributing to the abstraction have not been significantly reduced to date (Beck and Bernauer, 2011; Uhlendahl et al., 2011; Beekman, 2016). For a city-centric scale of Lusaka the nexus resources are dependent on water from the Kafue River for their production (Beck and Bernauer, 2011; Cervigni et al., 2015).

The Lusaka Water and Sewerage Company (LWSC) manages the formal water supply to the city of Lusaka. The formal water supply is from the Kafue River and the Lusaka groundwater aquifer and is treated at the Iolanda water treatment works. Iolanda currently has water rights to abstract 200 000m^3/day from the Kafue River, it currently has a design throughput of 110,000m^3/day; however the age of facilities makes the working ratio of the water plant is approximately 95,000 m^3/day (JICA, 2009; Millennium Challenge Corporation, 2011). Demographic changes in the city of Lusaka such as the growth of the population and the urban and peri-urban distribution are important influencers in the future resilience of water supply as they determine the socio-economic living conditions of the population. The population of Lusaka has nearly tripled since the independence era and is one of Africa's fastest growing cities (Pegasys and WWF, 2016). **Figure 2-7** illustrates that the availability of water per capita in Zambia far exceeds the per capita withdrawal. Although the growing population increases the stress on the water supply system, it is often not supported by growth in the water supply services.

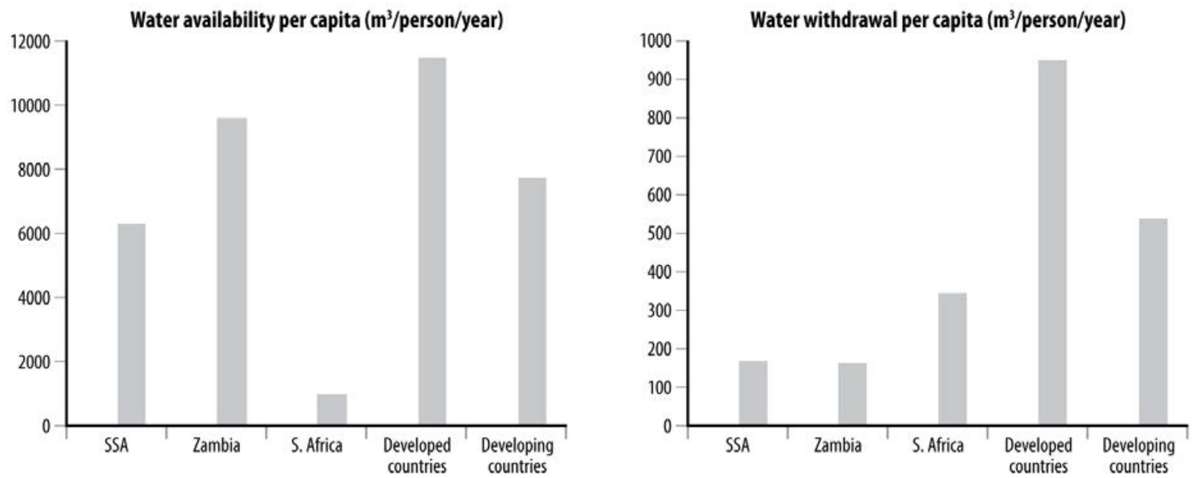

Figure 2-7: Per capita water availability and water withdrawal (World Bank, 2009)

In Zambia, and specifically the Kafue Basin, groundwater is used for both urban and rural water supply; however, surface water is the dominant supply source for the basin. The Kafue River has the greatest water demand in Zambia, with regards to water rights and water abstraction (Beekman, 2016). The area of the basin near Lusaka and the Copperbelt include groundwater aquifers; these are limitedly exploited (Department of Energy and Water Development 2007). In addition to the surface water abstracted from the Kafue River, LWSC abstracts groundwater from the Lusaka aquifer which covers an area of approximately 300km^2 with a total of 72 boreholes in operation of which 10 are large production boreholes (Japan International Cooperation Agency, 2009). The inadequate quality and low level of reliability in surface water resources has led to the Department of Energy and Water development to consider the development of groundwater supply as a useful future option. In Lusaka, borehole drilling and abstraction of Lusaka's groundwater resources has increased due to population growth, economic development and variable rainfall (Beekman, 2016); this increased use affects LWSC as approximately 55% of its supply is from groundwater sources.

In addition to formal water supply, the considerable number of peri-urban areas within the city of Lusaka needs consideration of the informal options for water supply. The 33 peri-urban areas in Lusaka account for approximately 70% of the city's total population. Inclusion of the informal water supply in the climate risk analysis is important to show where trade-offs between formal and informal supply can be implemented and which supply system is more vulnerable to changing climates. The informal water supply systems include private borehole abstractions, LWSC satellite water supply system such as the Water Trusts and private schemes operated mainly for peri-urban areas and not connected to the major distribution network, water from rivers and streams and water collected through rainwater harvesting.

Accurately assessing the current groundwater potential of the country is difficult due to a lack of data. Abstraction from private boreholes is estimated from 3,000-4,000 points (JICA, 2008). In addition to the satellite and bulk water supply systems the peri-urban areas in the city receive water from a community-based organization known as Water Trusts or Private Schemes; there are 12 Water Trusts in the city under the supervision of the Lusaka City Council (LCC). These Water Trusts have an average water supply of approximately 5,500 m^3/day (JICA, 2009) of which it is estimated that 60% supplies the water kiosks and the remaining 40% supplies public standpipes and on-site taps. Majority of the water trusts lack formal systems for the monitoring of the groundwater that they abstract their supply from. The contribution to supply made by water from streams and rainwater harvesting was considered negligible in the current state of the Lusaka water supply system but the inclusion was vital to the future analysis of the trade-offs between supply options. As an important freshwater source in many parts of the world, namely Lusaka, the global decline of groundwater levels can be a symptom of water scarcity (Cooley et al., 2014, p.2).

Surface water from the Kafue River, specifically from the Kafue Flats, has been identified as a major source for potential future supplies. Bulk water volumes from the Kafue River can be can be easily conveyed, and there is the potential for future abstraction quantities to meet the future demands. This can be achieved if the operation and maintenance of the existing treatment plant are optimized. Lusaka has a high amount of non-revenue water lost from the supply system due to leakages or inadequate licensing; majority of which occur in the Kafue pipeline (Gauff Ingenieure, 2013). These losses result in loss in revenue and increased demand numbers. These losses need to be minimized before future demand can be apportioned. As a result, one of the greatest challenges to establishing resilient water security is an infrastructure capacity constraint as oppose to a resource constraint.

3 METHODOLOGY

3.1 Methodological approach

The methodological approach of the research is predominantly based on quantitative outputs., as the research aims to establish theoretical associations between identified variables (Fisher and Reed, 2012). A quantitative approach was chosen as looking at the city-regional scale of a water system uses a wide range to capture information (Fisher and Reed, 2012). The approach is both inductive and deductive as some factors, such as climate and socio-economic changes were identified as important and only those were used to observe patterns that emerged from their inclusion in the research aim. The adaptation decision-support framework applied, decision-scaling, uses a bottom-up approach which involves stakeholder engagement; however, findings from these engagements were used to obtain quantitative and institutional information.

Both ethical clearance and a travel authorisation and risk assessment form were completed for the research. No ethical risks were identified as the "workshop" process envisaged includes participants that have all given their informed consent and who have the right to withdraw at any point. As a component of the broader FCFA project all participants have been cleared for participation by the FRACTAL consortium partners. The outputs of the research will be available for verification by the "workshop" participants and plagiarism will be avoided. A desk study was carried out which included the literature review, and analysis of existing hydrological models for the study region.

3.2 Overview of decision-scaling method

Decision-scaling is a bottom-up adaptation framework used to identify a system's resilience in the context of stakeholder-defined needs. The method finds the climate and non-climate stakeholder-defined vulnerabilities or "breaking points" in the system and then finds solutions that perform robustly for a wide range of future scenarios. The framework identifies climate changes as potential stressors that could result in risk and then identifies the likelihood of said climate changes using projections. The system performance metric "breaking points" are the basis of the water supply stress test in this study and are used to find the "safe space" in which decisions can be made.

The framework promotes the use of climate adaptation designs that can be flexible, robust and efficient. For this study an adapted version of decision-scaling developed by Poff et al. (2015) was used. The adapted framework includes other system metrics in addition to climate change to test the system sensitivities and assesses the performance of proposed adaptation measures against a set of stakeholder-defined thresholds for more robust decision support (Poff et al., 2015). The framework helps in developing techniques that iteratively reduce system vulnerabilities; while providing a consistent, credible and repeatable process to assess climate risks (Ray and Brown, 2015). There are four stages to the framework (**Figure 3-1**); the first 3 stages pertain to risk assessment and the fourth stage pertains to risk management. The decision scaling framework can improve the transparency of the water management decision-making process by integrating socio-economic objectives with a range of future climates for a vulnerability assessment of a water supply system.

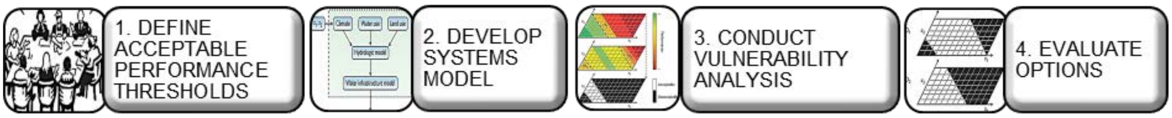

Figure 3-1: Decision scaling framework used adapted from Poff et al. (2015)

Decision-scaling was developed as a tool to holistically explore the water resource risks to bridge the resilience-robustness gap. The framework is an effective means of balancing many concerns and risks due to its stakeholder-driven aspects (AGWA 2017). Correctly applied, the decision-scaling framework can meet both social and ecological needs as a robust method of sustainable water resource management in an uncertain, complex future. It has been chosen as the primary climate adaptation tool for the water resource analysis. The design behind the decision-scaling process is such that it transforms climate information to be both relevant and useful for risk assessment and decision making (Brown, 2011).

The framework focuses on predicted vulnerabilities rather than examining a wide range of scenarios, which promotes communication with stakeholders to establish what anticipated vulnerabilities might be (AGWA 2017). It does not rely on future scenarios, which is necessary in an African context, as future scenarios are difficult to determine for developing countries. This makes this type of bottom-up analysis ideal for adapting to vulnerabilities that are difficult to quantify. Human decisions on the implemented water systems will have both short and long-term impacts on the resilience of the water supply for the city of Lusaka; highlighting the importance for the decisions to incorporate adaptation frameworks.

3.3 Step 1: Defining acceptable performance thresholds

Performance indicators are the values or services identified as important by stakeholders (Poff et al., 2015). These can be mapped in a climate space to detect the conditions under which the system does not adhere to stakeholder and decision-maker defined thresholds.

3.3.1 City learning labs

Lusaka city learning labs (learning labs) were stakeholder engagements used to define their interests and acceptable performance metrics. Learning Labs have the same principles as social labs which engage with a vast group of stakeholders to find solutions for a perceived relevant and urgent specific problem (Hassan, 2014). They are based on active participation of the stakeholders to design potential solutions in a systemic approach. Through engaging with a broad and diverse group of stakeholders for a specific problem the participants of the learning lab are encouraged to share their opinions and needs (Polk, 2015; Arrighi et al., 2016). The city learning lab was used as a platform to find the critical issues faced by a group of stakeholders in the city of Lusaka, Zambia. This platform created dialogue and, through a facilitated process, investigated the various sides of the critical issues and led to discussions about possible solutions. The learning process is iterative and looks to explore the climate information that could be used in decision-making structures within the city of Lusaka.

A stakeholder-driven structure of decision-scaling is effective in balancing multiple concerns and risks. The framework uses a user-centred participatory approach in which climate change risks are incorporated into decision making (Poff et al., 2015; Ray and Brown, 2015). A series of learning labs were held with decision-makers and informants from the city of Lusaka (NWASCO, Lusaka Water and Sewerage Company, Lusaka City Council); from academia (the University of Zambia, the University of Cape Town) and research institutions (UK Met Office, Red Cross Climate Centre). The first learning lab co-explored critical issues for the city of Lusaka with some key stakeholders, the embedded researchers, local and foreign academics, and city partners. This process found water supply (specifically in peri-urban areas) and flooding as burning critical issues for the city. As stated in the introduction, water supply was chosen as the focal critical issue. The second learning lab, included a climate workshop, development of the water system diagram to define the system performance thresholds, a high-level breakfast, and a field trip to a peri-urban area. The participatory element of the research method aims to foster knowledge and skill sharing so that the research outcomes reflect the needs of the decision makers.

3.3.2 Data sources

To fully evaluate water resources, datasets are needed. These datasets should show changes in both frequency and magnitude of climate conditions and extremes. To better predict how water resources will be affected by changes in climate, climate and demographic processes needs to be better understood to improve the estimation of their impacts on water resources. Weather and climate and demographic information should be used as a principal element for risk management (Department of Energy and Water Development, 2007). Ideally modelling of a water system should be carried out using hydrological and land-use data; however, due to the time constraints and to minimise uncertainty a calibrated surface flow hydrology outputs from the Zambezi Decision Support System (ZDSS), developed by Pöyry Energy (Kling and Preishuber, 2013; Kling, Stanzel and Preishuber, 2014; Spalding-Fetcher et al., 2014; Spalding-Fecher et al., 2016), will be used as a data input for the water resource system modelling.

The dataset is in the public domain and has been calibrated using streamflow data for the Zambezi sub-basins. The runoff outputs from the ZDSS model give surface inflow inputs for the Kafue River near the city of Lusaka and includes runoff from irrigated agriculture and natural vegetation. The advantage of this data source is that it has already been tested against observed historical flows at streamflow gauges. The model also allows for the extraction of the underlying precipitation, temperature, and evaporation data. Other modelling assumptions were based on existing literature of African urban water use and the local water supply investment master plan. Making changes to climate and socio-economic components of the input data, the system vulnerabilities can be tested.

3.4 Step 2: Developing a systems model

A systems model is developed or acquired to assess the water system's response to varying inputs. Process based models are one of the most commonly used quantitative tools for assessing the impact of climate variables, such as temperature and precipitation, on water resources (CDM, p 5-8). A process-based model simulates the physical processes that the actual water resource experiences and is a commonly used quantitative tool to assess the climate variable impacts on water resources (CDM, 2011). According to CDM (2011) the models use mathematical formulas to quantitatively estimate the effect that the water resource system will have to changing variables. To adequately run these models, sufficient data is required for the underlying physical processes to be understood and mathematically represented. Once the model is established, it should ideally be able to simulate responses for a wide range of changing climate conditions that tests the vulnerability of the system.

3.4.1 Modelling hydrological processes

The Water Evaluation and Planning Tool (WEAP) was chosen as the primary tool to model potential climate effects on water resources in the city of Lusaka. WEAP is an integrated water resources planning tool used to represent current conditions in a specified area (Cervigni et al., 2015). The tool allows the exploration of demand and supply options to balance both environmental and development goals. WEAP was used in the context of the decision-scaling climate planning method to model the changing responses of the system. This was achieved through the development and assessment of a variety of scenarios that represented possible futures for Lusaka's water resources. The model gave a platform for the investigation of the impacts that potential physical changes will have on the water resource system. The Lusaka water resources were modelled in WEAP as a basic model; this meant that the water supply system was simplified into an applicable format for WEAP, based on the co-developed outputs from the Lusaka learning labs. This resulted in some accuracy of the system being lost. Where modelling gaps existed, empirical simplifications were used.

A hydrologic-water system rainfall-runoff model such as WEAP can be used to conduct stress tests and analyse the water systems vulnerabilities. As a lumped model, WEAP suffices for the modelling of smaller catchments as they can be quickly built and run. A lumped model does not have geographic heterogeneity, the features of the watershed being modelled are represented at a point. WEAP incorporates demand side management into a practical tool for policy analysis and water resource planning. The tool can simulate both natural and engineered components of water resource systems. The WEAP configuration can be simply constructed, viewed and modified using the geographic information system-based graphical interface. Although the complexities of real-world water systems cannot all be represented using models that explore known system vulnerabilities (Groves et al., 2014), conceptual models are used because of their speed, simplicity and accuracy. Using a model that can generate several realistic climate change scenarios will drive a vulnerability assessment.

There is a common approach, as described by Cervigni et al. (2015), in developing a WEAP model that will be adopted in this study. The first step is spatial extent and the area system components definition. This definition includes creating the network configuration. Developing the WEAP model includes setting a time horizon, noting that most planning exercises have a time frame of analysis that does not extend more than 50 years into the future (Brown, 2011). The second step in developing a WEAP model is defining the current accounts of the system as a baseline representation and development of scenarios by characterising alternative future assumptions. An initial model and future scenarios will be developed based on existing literature, output data of the ZDSS model developed by Kling,Stanzel & Preishuber (2014), and outputs from the Lusaka city learning labs.

The final step in developing a WEAP model is the evaluation of the model. The existing Zambezi basin WEAP model (The World Bank, 2010) water is generally allocated in the following order of priority: domestic use, environmental flow requirements, irrigated agriculture, hydropower generation and reservoir storage (Cervigni et al. 2015). This structure reflects the realities of water management and usage in the basin. Using mathematical formulas to approximate the effect to the system when variables are changed, a process-based model simulates the physical processes of the real world (CDM, 2011). A configuration of the water system for the city of Lusaka as part of the Kafue River Basin will be developed, using WEAP, as a tool to test the system sensitivities.

3.5 Step 3: Conducting a vulnerability analysis

The system's performance weaknesses to changes can be explored with the use of a system stress test. The stress test is a process whereby a given option is tested against a range of possible climatic and non-climatic variations to identify system vulnerabilities. These variations can include changes in means and other aspects of variability. The system's response to changes in climate and non-climatic inputs and the associated risks should be assessed. The vulnerability analysis considers the risks associated with the changes of the performance indicators and thresholds. Through the definition of a number of ex-post scenarios a system's performance can be explored using coupled climatic and non-climatic factors (Ray and Brown, 2015). Water supply stress tests identifies system vulnerabilities through iterative change of climate and other input parameters to simulate possible future conditions without identifying which future is more likely than the other (Groves et al., 2014; Poff et al., 2015; Ray and Brown, 2015). The WEAP model will be repeatedly run, for multiple climate and socio-economic changes, these potential changes are named as system stressors.

Water resource projects are subject to variable risks on both the supply and demand side. The risks associated with the supply include climate change. These changes may be based on changes in precipitation quantity, timing or intensity; increasing temperatures or increased evaporation; environmental degradations or upgrades; or a change in the manners in which the water resources are distributed (Ray and Brown, 2015). Demand side pressures include, but are not limited to, population growth, urbanization, a shift in agricultural and irrigation patterns, or increased environmental water demands. System stressors are images of how the future may look and are tools to analyse driving forces and the associated uncertainties; however separating the impacts of climate and socio-economic stressors is difficult (Calow et al., 2011).

3.5.1 Climate stressors

The manifestation of climate change in the water cycle is complex because precipitation varies in the form of Mean Annual Precipitation (MAP), seasonal variation (seasonality), flow variation (inter-annual variability) and precipitation intensity (percentages) (García et al., 2014). To fully understand the effects of climate change on water availability for urban communities the capability should exist to predict average rainfall, streamflows, extreme flows, storms and potential changes in groundwater yields. Prediction of rainfall patterns is imperative to decision makers, specifically in an African context, as they are dependent on natural resources, agriculture and tourism which changes in the patterns would greatly impact (Jones et al., 2014). Because a city-centric approach was adopted, only stressors considered directly relevant to city stakeholders were included.

The climate and non-climate risks related to future uncertainties must often be addressed by decision makers. To illustrate the effects of these risks within the context of climate vulnerabilities the concept of climate narratives will be used. Climate narratives take an exploratory approach to impacts analysis without extensively modelling the climate impacts. Impacts analysis explores the co-behaviour of the tested climate variables as variations may not necessarily occur independently and would have compounded effects.

The Water Utility Climate Alliance (WUCA) produced a white paper in which the relative appropriateness for the application of climate model variables to various water management issues were identified. **Table 3-1** highlights components of the white paper (CDM, 2011). The highlighted row shows that annual mean temperature and precipitation are the climate variables most likely to affect long-term supplies for mean annual basin yield, which this study focuses on at a city-regional scale for the Kafue Flats.

Table 3-1: Climate model variables relevant to water management issues

Water Management Issue	Climate Model Variable
Long-term supplies for mean annual basin yield	**Annual mean temperature and precipitation**
Long-term demand	Warm season temperature and precipitation
Shift in seasonality of runoff	Seasonal precipitation
Long-term supplies for variability in yield	Monthly temperature and precipitation

3.5.2 Socio-economic stressors

Other long-term planning indicators and non-climatic system stressors can also play a role in system vulnerability as they have their own associated uncertainties. Non-climate stressors can have a greater impact on water resources than climate-related hydrologic changes (Groves et al., 2014). Due to the difficulty of predicting which drivers contribute to vulnerabilities in water resources, stressors will be limited to quantifiable drivers. Planned demographic and water use changes will be used as non-climatic socio-economic stressors to the water supply system. Stressors include:

- Percentage of water lost as non-revenue water. These losses include losses in the billing process of metered and unmetered consumption, apparent losses from unauthorised consumption and metering inaccuracies, and real losses from leakages and storage tank overflows (Japan International Cooperation Agency, 2009).
- The total population as future demands are proportionate to increasing population:
- Peri-urban and urban population distribution: water consumption is not fully understood but a theory can be made based on levels of accessibility and reliability of a water service (Purshouse et al., 2015). Often cities lack the infrastructure capacity to supply adequate volumes of water to meet demand, and factors such as distance to the source, queuing time and inflating sale prices at water kiosks affect the water demand per capita (Purshouse et al., 2015).
- Land use changes, specifically agricultural: the strategy for flood management of the Kafue River Basin proposes that the ministry of agriculture and cooperatives develop, support, and encourage flood resistant crops and cropping patterns that would help income growth. The National Agricultural Policy (NAP) encourages the diversification of the production and utilization of agriculture.

- Hydropower infrastructure expansion: Plans for both rural and urban development include the development of substantial hydroelectric power. This development would give a tool for enhancing activities in the Kafue River Basin as well as provide affordable electricity for uses such as irrigation and industry (Department of Energy and Water Development 2007).

3.6 Step 4: System evaluation

Estimating the risk of the exceedence of critical impact levels for climate related adaptation strategies is essential (Grijsen et al., 2013). Identifying these risks provides insights into the plausibility of a specific climate change which allows for informed adaptation decisions. The spatial and temporal scales of climate projections, which are relevant to water resource planning, tend to lack the required level of detail, even though there are downscaling approaches available capable of changing the spatial resolution of the projections (Grijsen et al., 2013).

Management actions will be used as narratives describing plausible system states using the literature review of national and regional development plans; and the city learning labs activities as guidelines. The model results will highlight how changes in non-climatic system stressors may carry higher risks for water supply and where trade-offs may be required to achieve urban system resilience. A step to manage and reduce the risk outcomes is to identify the simplified relationships between the climatic and non-climatic stressors and address the capacity of the system to achieve resilience for the greatest set of variability.

3.6.1 Defining system vulnerabilities

Adaptation decision-support should provide responses to recover from external impacts, i.e. to be resilient. Adaptation in the water sector cannot only be focussed on water, as water insecurity triggers other variations which require sound governance and institutional frameworks (see **Appendix A**); and in the case of Southern Africa, this includes infrastructure development. To evaluate the city-regional water system and its vulnerabilities, the Four C's framework (Ray and Brown, 2015) for guidance; the Four C's are **C**hoices, **C**onsequences, **C**onnections and un**C**ertainties. This framework identifies:

i. City-regional **choices** regarding their water supply

ii. **Consequences** to evaluate water security

iii. Linkages and **connections** between different choices

iv. Highlighting **uncertainties** that could affect resilience

The Four C's framework helps to qualitatively identify where the system may be most affected and explores the system in context (Ray and Brown, 2015). The research by Ray and Brown (2015) uses the Four C's to find if the project has climate sensitivities however in the scope of this research they were used to highlight focus areas for resilient water security.

3.6.2 Unpacking urban water resilience

The evaluation and the recommendations for resilience were cross-cutting. Measures for resilience considered the levels of perceived resilience (Johannessen and Wamsler, 2017); namely:

Socio-economic resilience: In an urban context, most applications for resilience are linked to socio-economic disturbances. Socio-economic resilience deals with risk associated with socio-economic, and institutional frameworks; this includes financing operation and maintenance institutional capacity gaps, debt increase and power dynamics.

Hazard resilience: this is resilience to external risks or hazards (e.g. climate) that are not institutional or linked to the service infrastructure

Socio-ecological resilience: these are long term risks (e.g. population growth that leads to unsustainable abstraction).

3.7 Method application to the research

A research method matrix was developed to ensure that each research objective and question had an associated component of research method (see **Table 3-2**).

Table 3-2: Research method matrix

Research Objectives and Questions	Research method				
	Literature review	Water data sets/ modelling	Learning labs	Vulnerability analysis	System evaluation
Obj. 1: Explore city-centric water system and the climate and socio-economic sensitivities and uncertainties of the system at a city-regional scale.					
RQ 1.1: What are the climate and socio-economic stressors to a city-regional water system?	Y		Y	Y	
RQ 1.2: How do city-regional sensitivities to change translate into city-centric impacts on a water system?		Y	Y		Y
Obj. 2: Quantify the vulnerabilities of African urban water security and its dependant sectors, due to external stressors, by developing a city-centric water resource model of the city of Lusaka reliant on the Kafue River Basin.					
RQ 2.1: What are the dependent sectors of African urban water security?	Y	Y	Y		
RQ 2.2: How can the vulnerabilities of a water system, and its dependent sectors, be quantified to inform resilience?			Y	Y	Y
Obj. 3: Inform short to medium-term decision-making by evaluating the water system's vulnerabilities, using an adaptation framework for decision support.					
RQ 3.1: How can vulnerable water systems be more resilient in the short to medium term?	Y				Y
RQ 3.2: What is the benefit of applying adaptation decision-support frameworks for water management?	Y		Y		Y

4 CASE STUDY RESULTS: LUSAKA AND THE KAFUE FLATS, ZAMBIA

4.1 Introduction

Water resource management is primarily dependent on two components, the first being the direct component of water supply and demand which considers all available water resources, how they are managed and how they can be best utilised to the communities. The second component of water resource management including land use and the surrounding environments is indirect. This includes environmental requirements, agriculture and urban development. **Figure 4-1** shows the study area which is downstream of Itezhi-Tezhi reservoir until, and including, Kafue Gorge Upper Reservoir and hydropower plant. The area includes the Kafue flats and the city of Lusaka.

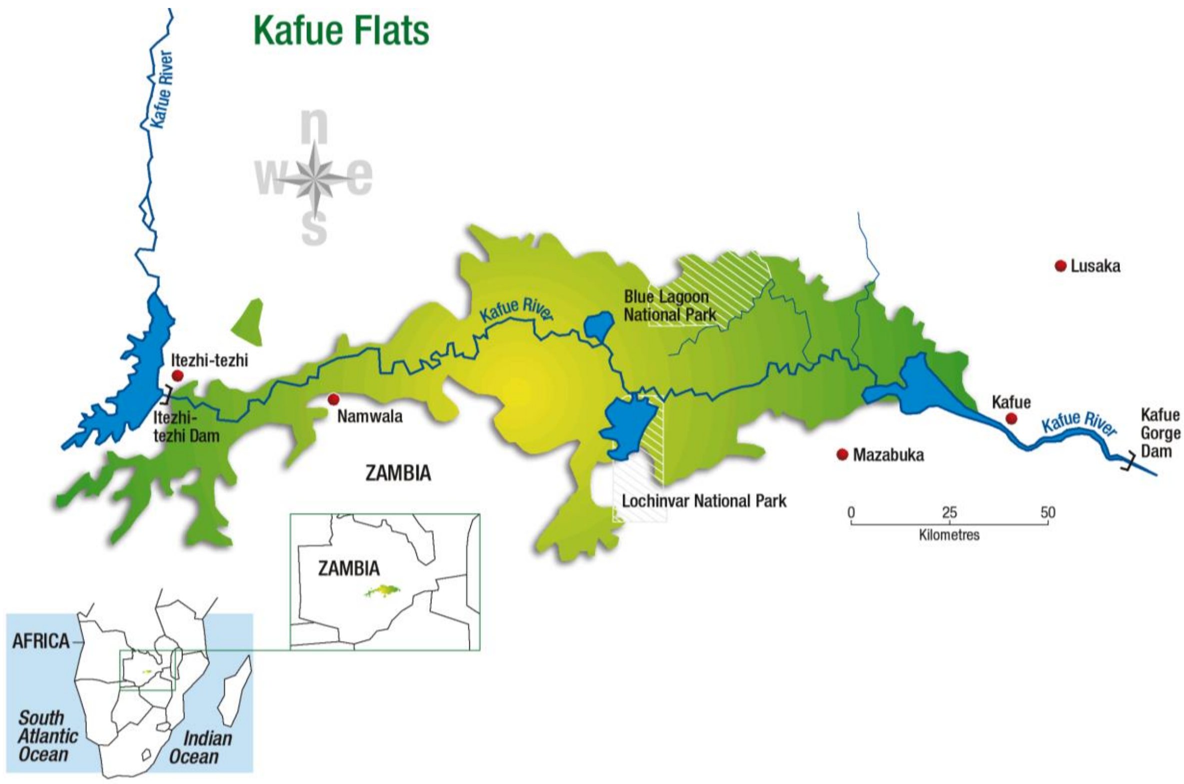

Figure 4-1: Study area (WWF, 2003)

The decision to use decision-scaling as the framework applied in this study was based on this method being used within the broader FRACTAL project; although several bottom-up decision support frameworks exist. Decision-scaling is both efficient and scientifically defensible, as it does not rely heavily on assumptions about a system's future, making it useful for risk assessments (Ray and Brown, 2015). Firstly, stakeholder thresholds were defined through city learning labs. Secondly a city-centric water system model for Lusaka, within the Kafue Flats, was built, using WEAP. Thirdly the system was stress tested to analyse the water security vulnerabilities to climate and socio-economic changes. Lastly the risk of the system was evaluated to inform resilient decision-making, which is elaborated on in the discussion.

4.2 City learning labs

The city learning labs (learning labs) were used as a platform for stakeholder engagement. They facilitated collaboration between researchers, university partners, city officials and civilians. Each of the attended learning labs played a key role in defining the acceptable performance thresholds as they focussed on dialogue. Through the learning labs burning issues were identified and discussions had on how they could be better managed and less vulnerable to climate variability in the future.

Learning Lab 1 (7 September 2016)

This section is based on secondary information but was valuable in defining the priority areas that were the focus of this study. Discussions were held on the impacts of the El Niño from which stakeholders felt that it had resulted in water shortages, low agricultural yields and load shedding based on decreased water levels of Kariba dam. The first learning lab aimed to identify a set of initial issues, research requests, develop ideas around climate related training and for the stakeholders to build networks with one another. A key session during the learning lab was identifying “burning issues” for Lusaka. In total, eight themes were initially developed which included water resource management issues, land use planning issues, and institutional practice issues; however, the priority was on water. One of the final burning issues, on which this research is based, is around the supply of water in urban and peri-urban areas of Lusaka. Other issues included groundwater recharge and, flooding and solid waste management.

Learning Lab 2 (6 July 2017)

The second learning lab brought the concept of governance and decision making to the foreground. The lab included presentations from: The Lusaka City Council District Planning Officer, National Water And Sanitation Council (NWASCO), Zambia Meteorological Department, and the University of Cape Town Climate Systems Analysis Group (CSAG).

The second lab also included a visioning process in which the participants developed a joined vision for where they saw the future of water in Lusaka. The proposed vision was “Accessible and affordable quality water for the present and future generations in Lusaka for all”; with planning and infrastructure being highlighted as key focus areas in which the city currently faced challenges. A key output of the second learning lab was beginning to develop the system’s model through co-production with the stakeholders at the lab (see **Figure 4-2**).

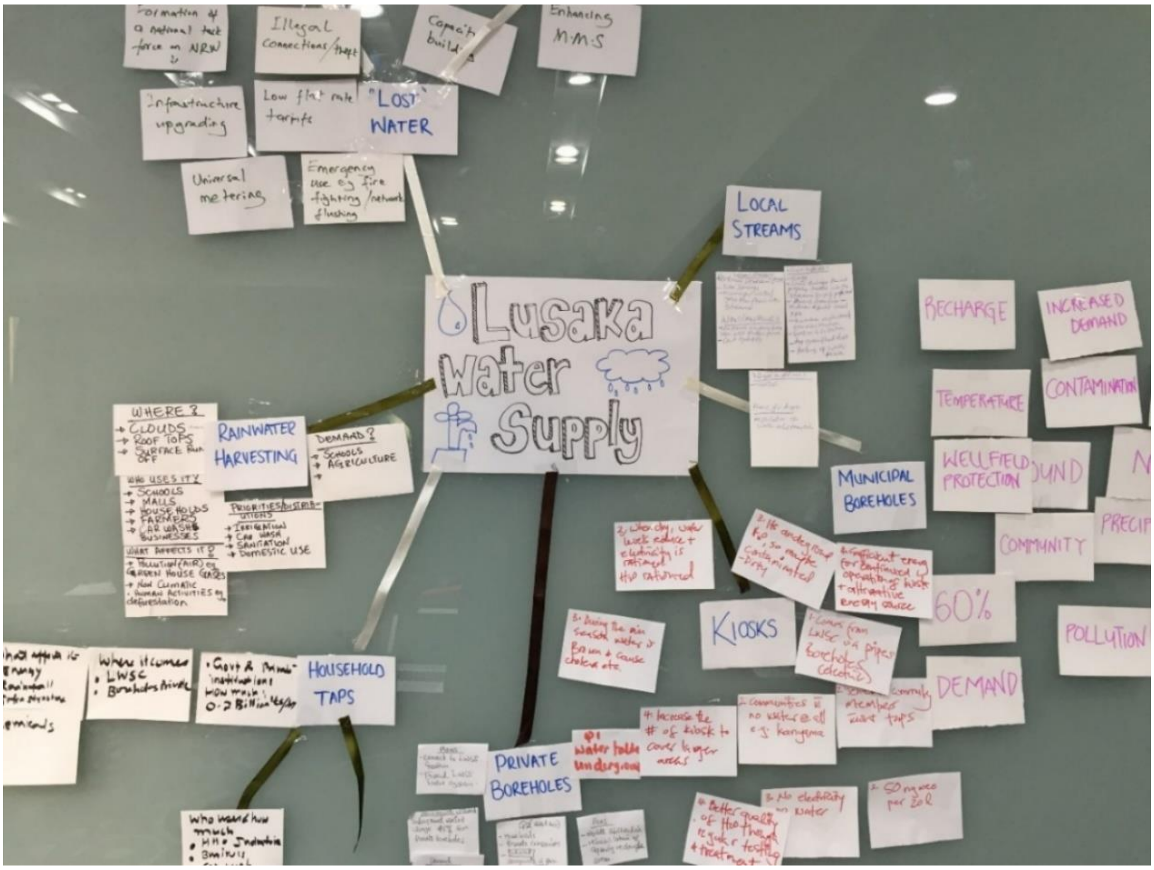

Figure 4-2: Co-produced mind mapping to inform systems model

Co-production took the form of mind mapping and questioning where water was sourced, who used it and how much and what climate variables were thought to affect it; the base components of the system's model were determined. The concept of a water supply stress test was presented, explaining how it aimed to develop tools that support and aid in decision-making through co-production. The concept of bottom-up frameworks was described, proposing ways in which climate responses within a city's water system could be evaluated to inform decision making. Stakeholders agreed that it would be valuable to know what water system elements are most important to map decisions.

Learning lab 3 (27-29 November 2017)

The third learning lab was valuable for developing a better understanding of how the existing infrastructure works. The lab included a field trip to Shaft 5 in Lilayi, which is one of the largest boreholes that supplies water to the city. As well as a field trip to Iolanda treatment plant in Kafue, which is Lusaka's water abstraction and treatment plant that gets most of its water from the Kafue River and provides approximately 40% of the city's water. Both field trips provided insight into the constraints of the existing infrastructure as well as plans for further development, expansion and resource protection. This learning lab gave an opportunity for stakeholders to provide feedback on the initial city-scale water systems model developed. Transdisciplinary thematic groups were formed for each of the city's burning issues (see Learning Lab 1). The water supplies thematic group focussed on showing who key policy recommendations were to be disseminated to, and how best to communicate climate risk narratives, the current state of water affairs, investment for future infrastructure development and key recommendations. To better understand the complexities of the water system and the associated decision-making frameworks, a systems analysis mapping exercise was held (see **Figure 4-3**).

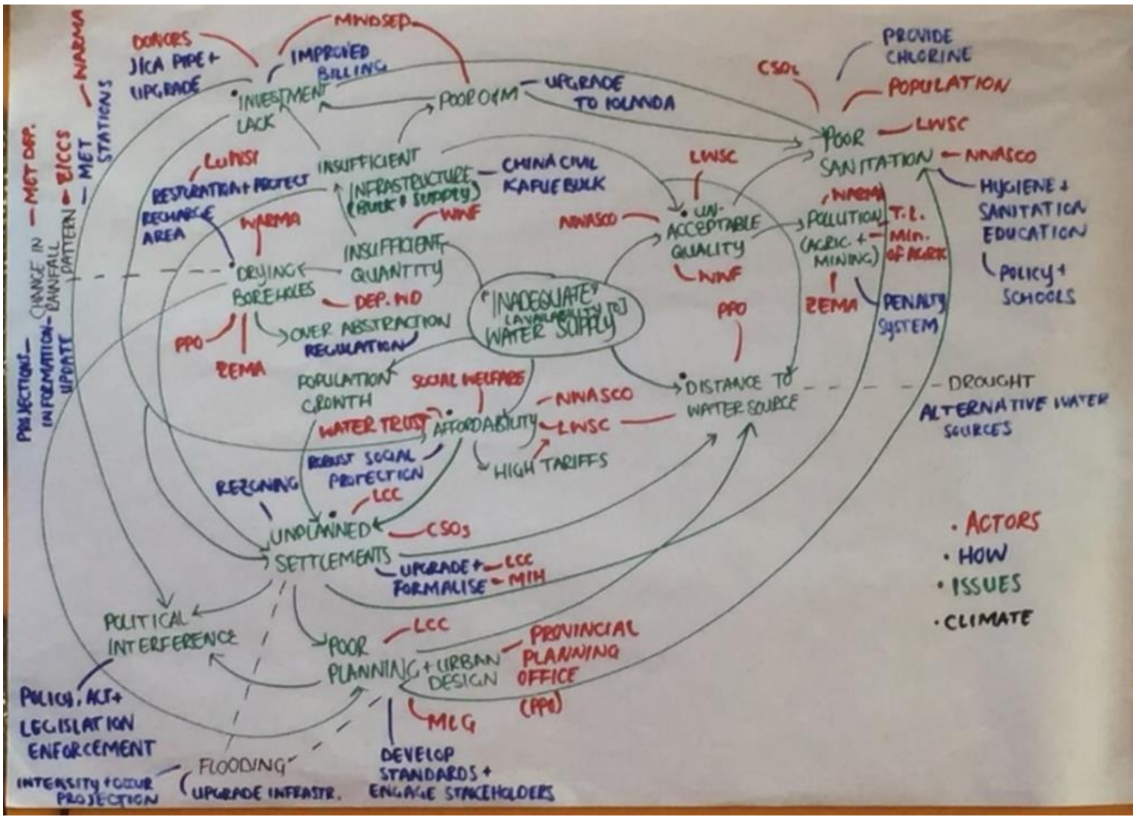

Figure 4-3: Co-exploration of issue and solutions for inadequate water supply in Lusaka

This exercise mapped out the actual and perceived causes of the issue of water supply with the goal of better understanding city systems and climate information needs. The exercise then transitioned into a solution mapping space and discussed which actors and capacities would be needed to deliver these solutions. Infrastructure development still emerged as a primary issue through this mapping process. However, the solutions and actor mapping provided insight into how, and by whom decision-making could be better informed. Future climate risk narratives (see **Appendix E**) and the societal consequences they would have were also discussed. The climate risk narratives (Jack and Jones, 2017) were developed for Lusaka and its co-dependent region(s); and informed the modelled climate variability for the water system's stress test.

Learning Lab 5 (13-16 November 2018)

The final Lusaka learning lab was used to gain final feedback on the city-regional model of Lusaka and the Kafue flats as well as to present the results of the vulnerability analysis. A distillation session was held to unpack the assumptions made and how they were informed as well as how altering those assumptions would affect the modelled system. Discussions were held about where resilience can be implemented in the short to medium term through LuWSI and its members. Determining the acceptably representative water supply system required stakeholder engagement and negotiation on what was acceptable (Chomba and Nkhata, 2016). Continuous engagement on articulating and discussing the dynamics of a water resource system and the competing interests within it, showed the complexities of water systems and their co-dependent sectors of energy and food.

4.3 Systems modelling for Lusaka and the Kafue Flats

A systems model was built using the Water Evaluation And Planning (WEAP) model (available at www.weap21.org). Building the model and setting a time horizon are the first step in developing the WEAP model. The model schematic for the city-scale and the city-regional scale can be viewed in **Figure 4-4** and **Figure 4-5** respectively The model used calibrated inputs from the ZDSS (Pöyry Energy GmbH and Kling, 2011) and the time horizon, was set up until 2035 from current day as the Water Supply Investment Master Plan proposes changes to water infrastructure up until then and most planning exercises have a time frame of analysis that does not extend more than 50 years into the future (Brown, 2011).

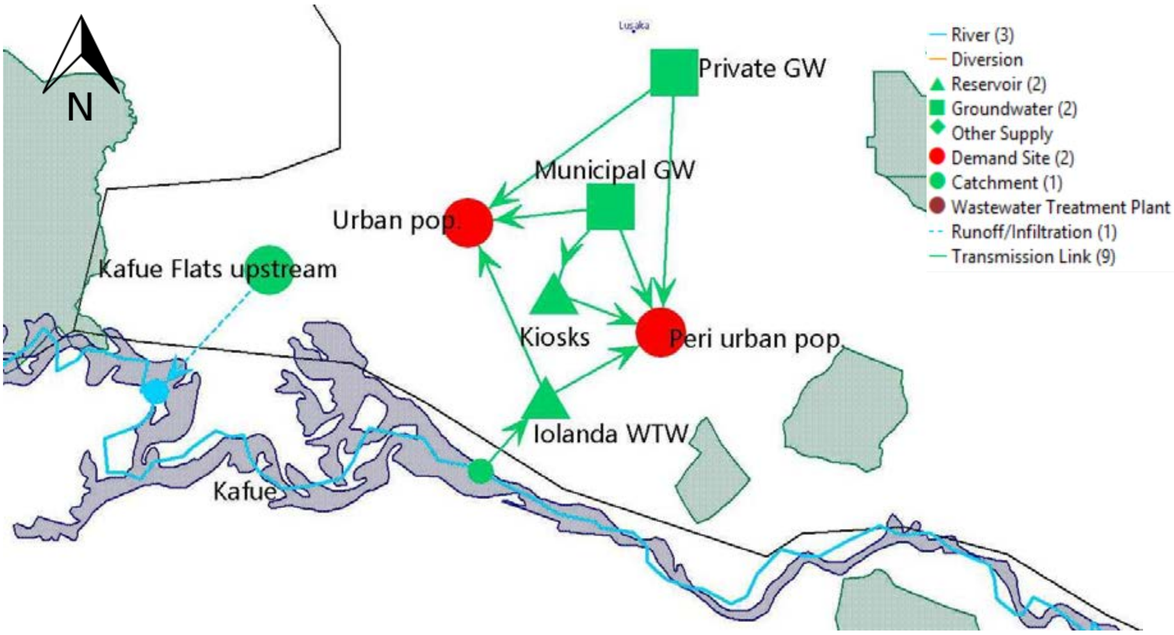

Figure 4-4: Lusaka city-scale WEAP schematic

The water-energy-food nexus is fundamental to the needs of the population of Lusaka. The nexus resources are transported into the city through a pipeline, from the hydropower plants, and from the rural agricultural surrounds respectively. The model focused on the demand analysis for hydropower demand (inclusive of reservoir evaporation), irrigated agriculture and urban demand as these are the current greatest demands from the Kafue Flats (WWF, 2017)

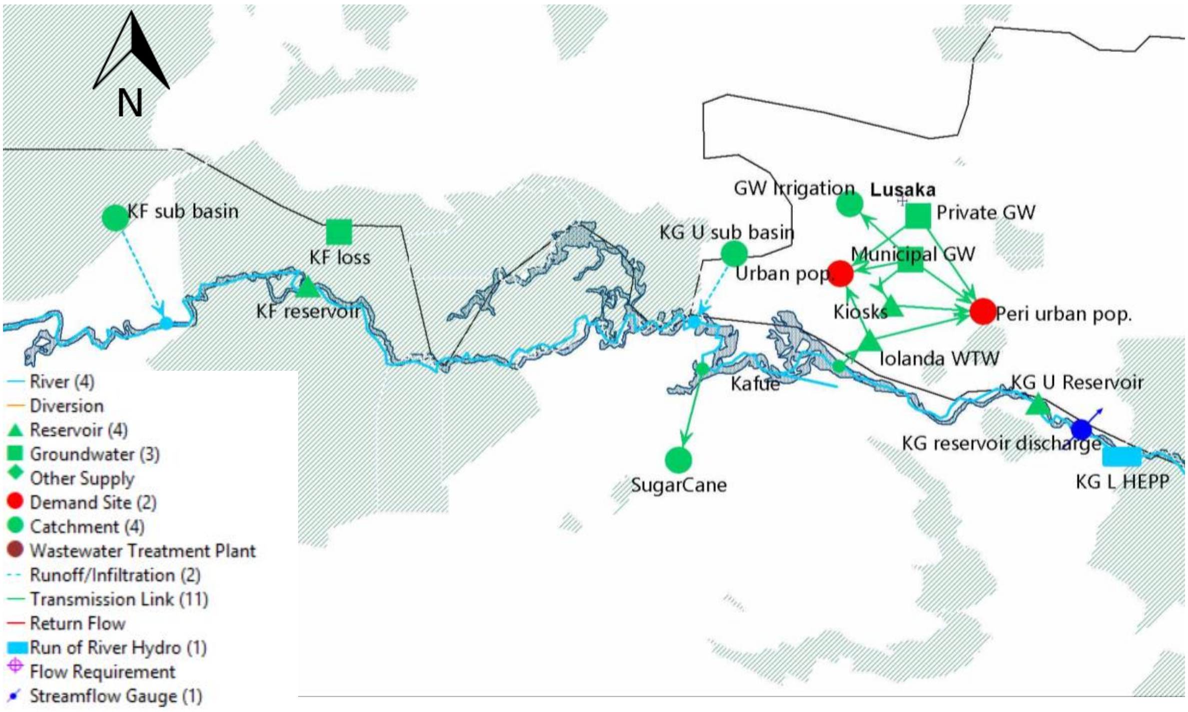

Figure 4-5: Kafue Flats city-regional WEAP schematic

The Kafue River basin, downstream of the Kafue flats and upstream of Kafue Gorge, and the Lusaka groundwater aquifer were the identified spatial extents as this is where the city of Lusaka demand is abstracted from and the water supplies recharged (see **Table 4-1**).

The urban water demand is driven by the population size and the urban to peri-urban distribution; the estimated demand per capita is taken from the Lusaka Water Supply, sanitation and Drainage Project (Gauff Ingenieure, 2013) and includes the commercial and industrial demands (equivalent to 50% of the per capita domestic demand (Nyambe and Feilberg, n.d., p.31). The urban domestic demand is estimated as 180 l/c/d and industrial demands at 90l/c/d; and the peri-urban demand at 60 l/c/d for domestic use and 30l/c/d for industrial use. In the case of the city of Lusaka the domestic discharge was not modelled as it was outside of the study area into the Luangwa River (Spalding-Fecher et al., 2014).

The second step in developing a WEAP model is defining the current accounts of the system as a baseline representation and development of scenarios by characterising alternative future assumptions. An initial model and future scenarios were developed based on existing literature, output data of the ZDSS model developed by Kling,Stanzel & Preishuber (2014), and outputs from the Lusaka city learning labs. The final step in developing a WEAP model is the evaluation of the model.

Figure 4-6 illustrates the baseline supply distributions for urban and peri-urban demands in Lusaka.

Table 4-1: Baseline (2017) extents for the water supply and demand of Lusaka

Variable	Value	Description and References
Lusaka Population	2426900	32.5% as urban and 67.5% peri-urban
Urban demand	270 l/cap/day	Average between medium cost housing and high cost housing capita consumptions for 2010 and 2015 (Ministry of Energy and Water Development, 2010, p.7; Gauff Ingenieure, 2013, p.2.14)
Peri-urban demand	90 l/cap/day	Average between low cost housing and informal housing capita consumptions for 2010 and 2015 (Gauff Ingenieure, 2013, p.2.14)
Total domestic demand	[(2426900 x 270 x0.325) + (2426900 x 90 x0.675)]/1000= 360 000 m^3/day	
Iolanda Kafue abstraction	105 000 m^3/day	Supplied Iolanda quantity 95 000 m^3/day (Millennium Challenge Corporation, 2011)
Groundwater catchment area	300 km^2	**Recharge area**:(Japanese International Cooperation Agency, 2008, p. 4-7) **Municipal Supply**: (Millennium Challenge Corporation, 2011)
Groundwater recharge	+6.3% MAP (Dec-Feb) -6.3% MAP (Mar-Nov)	**Private Boreholes**: average of 80000-26000 m^3/day (Japanese International Cooperation Agency, 2008, p. 4-8) **Water trusts** (of which 60% goes to water kiosks) (JICA, 2009, p.2-25) **Recharge distribution**: (Japan International Cooperation Agency, 1995, D-72)

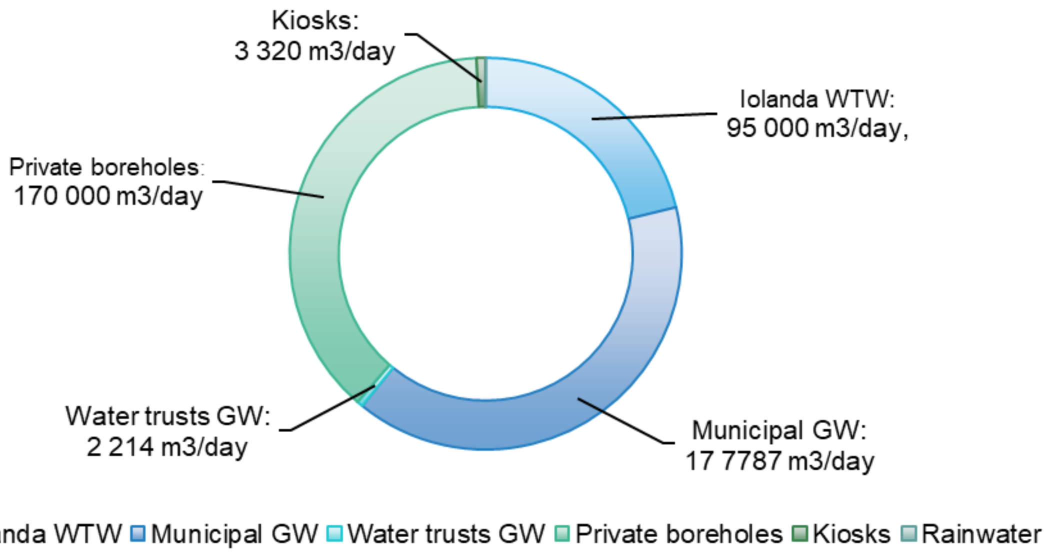

Figure 4-7: Baseline supply distribution for urban and peri-urban Lusaka

The city-regional model of Lusaka and the Kafue Flats had the same base level of detail as the ZDSS model downstream of Itezhi-Tezhi reservoir and up to and including the Kafue Gorge reservoir, see **Figure 4-5**. Additions were made for the city of Lusaka- which included groundwater; and irrigation abstraction for Zambia Sugar. Although groundwater is pivotal to the water supply of Lusaka, modelling of groundwater replenishment was limited to linear recharge (JICA, 1995) and the remainder of rainfall-runoff flows were treated as surface water in the Kafue. The scope of the study did not allow for detailed modelling of the entire Kafue river basin and a static model was assumed up to and including the discharge from Itezhi-Tezhi to the Kafue flats. In addition, other agricultural, domestic and industrial use within the Kafue flats were assumed negligible in comparison to that of Zambia sugar and the city of Lusaka.

The Kafue Flats wetland was modelled as a reservoir using the discharge-storage volume relationship from the ZDSS. The other modelled characteristics of the Kafue flats can be reviewed in **Appendix D**. The irrigation abstraction point for Zambia Sugar was modelled as an irrigated catchment without a return flow as this was assumed to be outside the study area. The water demand for irrigation was a function of the crop type, irrigation area, precipitation, and evapotranspiration.

The WEAP model determines if the effective precipitation to the irrigated area is sufficient based on the crop requirements; rainfall in excess of the effective precipitation becomes runoff and if the effective precipitation is not sufficient water is abstracted from the available water sources. The modelled crop type and area is based on the Multi Sector Investment Opportunities Analysis (MSIOA) study by the World Bank (The World Bank, 2010). The reference evapotranspiration for the modelled sugarcane was based on the potential evapotranspiration (ETo) extracted from the ZDSS mode, which is a function of temperature.

The flows needed to meet the specified hydropower demands are determined by the WEAP characteristics of the reservoir (Kafue Gorge Upper) and run-of-river (Kafue Gorge Lower) plant based on its required energy production. The energy production is therefore dependent on water availability and water demands upstream and downstream of the hydropower plant. Water is discharged through the plant spillway when maximum turbine flow is reached.

All the modelled demands were given the same priority, i.e. urban demand, irrigation demand, hydropower generation and reservoir filling; this was to isolate the sectors and see where trade-offs between them existed. Because the calibrated ZDSS model was used for WEAP inputs, to verify that the model was correctly simulating the originally modelled flows after the urban and irrigation demands had been included in the model, the simulated discharge, and the calibrated discharge downstream of Kafue Gorge Upper reservoir were compared.

4.4 Water supply stress test

4.4.1 System stressors

Due to the difficulty of predicting which drivers would contribute to vulnerabilities in water resources, stressors were limited to quantifiable drivers. Planned demographic and water use changes were used as non-climatic socio-economic stressors to the water supply system.

Socio-economic

Three socio-economic stressors were identified based on changing demographic and water use (Figure 4-8). The first was the peri-urban population distribution as a percentage of the total distribution, this was relevant to the supply system as the peri-urban population was modelled to have a smaller water demand per capita and a different water supply system when considering the formal and informal supply systems in comparison to the non-peri-urban (urban) population. The second demographic water use stressor was the percentage of water lost as non-revenue water. These losses include losses in the billing process of metered and unmetered consumption, apparent losses from unauthorised consumption and metering inaccuracies, and real losses from leakages and storage tank overflows (JICA, 2009). The total population is the third demographic water use stressor of the water supply system as future demands are based on increasing population. The estimated population growth rate for Lusaka is based on the 2010 census data estimates a 4.9% increase from 2010-2020 and a 3% increase from 2020-2035 (Gauff Ingenieure, 2013).

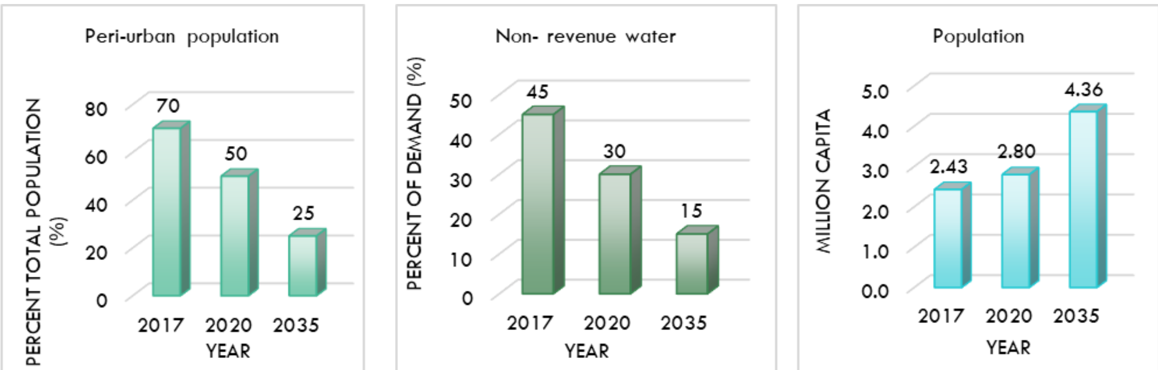

Figure 4-8: Demographic and water use changes for water supply system stressors

Climate

Because a city-centric approach was adopted, only stressors considered directly relevant to city stakeholders were included. Based on the co-developed outputs of the city learning lab local changes in MAP over the city of Lusaka and regional changes in mean annual runoff (MAR), upstream of the Lusaka abstraction off the Kafue River were chosen as the climate system stressors that would potentially have vulnerability risks for the Lusaka water system. **Table 4-2** includes a description of the climate stressors and the variation ranges from the respective historical monthly means in Lusaka as modelled in ZDSS that were used to stress test the water supply system. By altering runoff and precipitation, the climate space definitions can be changed. The model was iteratively run by applying the change factors to the baseline (1961-1990) regional precipitation and temperature. The range of these intentionally variable to not limit the extents of the risk map.

Table 4-2: Isolated city-scale climate change system stressors for water supply

Climate Stressors	Description	Range
Regional change in MAP	Local MAP over the Kafue flats region affects vulnerabilities of groundwater aquifers recharge (on a mean monthly basis)	-50% to +50%
Upstream change in MAR	MAR is an implicit function of evaporation and precipitation, which affects the abstraction sensitivities of model MAR downstream of Kafue flats (on a mean monthly basis)	-25% to +25%

For the regional model of the Kafue flats, the alternative climate futures consider a hotter future and both a wetter and drier climate, from increases and decreases in mean annual precipitation over the Kafue Flats region (see **Table 4-3**)

Table 4-3: Isolated basin-scale climate change system stressors for water supply

Climate Stressors	Description	Range
Regional change in MAP	Local MAP over the Kafue flats region affects vulnerabilities of the Kafue river streamflow, the change in reservoir storage and the irrigation demand (on a mean monthly basis)	-20% to +20%
Regional change in Temp.	Evaporation is a function of temperature and affects the reservoir storage volume and the irrigation demand (on a mean monthly basis)	0ºC to +3ºC

Historical climate data from the 1960's-1990s were used to populate the model as this is the period with the highest number of water and climate data reporting stations (Spalding-Fecher et al., 2014). These climate stressors included potential climate futures, but their ranges also included less likely climate futures to further highlight system vulnerabilities.

4.4.2 Management scenarios

This research used a management scenario approach for both the development inputs into the model. These scenarios were either on a city or a basin scale and considered socio-economic development futures which excluded the socio-economic stressors of population growth and distribution between urban and peri-urban populations, which influences water demand. The socio-economic development will include irrigation and hydropower expansion.

City-scale development

The details of the water resource management national acts and policies and guidelines outlined for Lusaka are not within the scope of this research. However, when investigating effects of system changes on water resources, these documents are at the basis of what would constitute negative and positive effects, forming the basis for threshold and hazard identification. Future available water resources depend on the acceptable performance thresholds identified, and the management actions i.e. scenarios that could potentially be implemented (**Table 4-4** and Error! Reference source not found.). Management actions are not predictions, they are narratives describing plausible system states. Three potential management actions, in addition to the system stressors, which vary from the current day baseline scenario were modelled to investigate the impact they could have on available water resources.

Each proposed management action, based on the Water Supply Investment Master Plan, was independently set up and run. The proposed management actions included made changes to the formal water supply off the main distribution system and did not consider community-based water supply schemes such as the water trusts, rainwater harvesting or private groundwater abstraction.

Figure 4-8 illustrates the potential total water supply for Lusaka if all the management actions were to be implemented up until 2035. It should be noted that the proposed management actions do not account for the associated shut down time that would be required for the increased capacity of the formal water supply systems. It is also assumed that the water received from the proposed development is of adequate quality.

Table 4-4: Proposed management actions for Lusaka city water supply (JICA, 2009; Gauff Ingenieure, 2013)

Management Actions	Description
Upgrade Kafue Pipeline	Upgrade Kafue Pipeline to 3200000 m^3/day total by 2017 (P1) Upgrade Kafue pipeline to 480 000 m^3/day by 2020 (P2) and; Maximize abstraction capacity to 640 000 m^3/day by 2035 (P3)
Increased boreholes	130000 m3/day total by 2010; 180000 m3/day total by 2017 (P1)

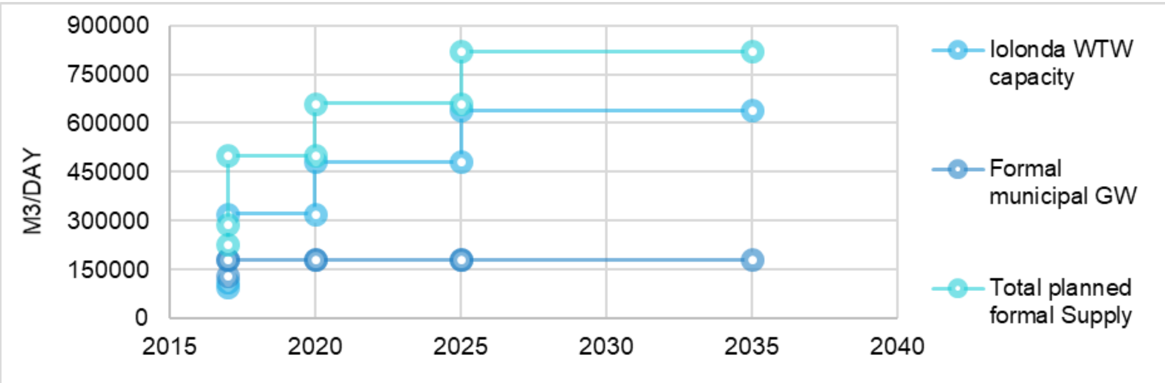

Figure 4-9: Lusaka total planned formal water supply (m3/day)

Basin-scale development

Due to the lack of an existing platform in which water users can share proposed projects and developments, determining projected water use and demand scenarios for the Kafue Flats is difficult (Chomba and Nkhata, 2016). As a result, sector development plans (Waltina Scheumann, n.d.; Godet and Pfister, 2007; Government of Zambia, 2017) were used as a basis for determining future water use and demand, which were largely focused on hydro-power, irrigation and domestic water use (Chomba and Nkhata, 2016). **Table 4-5** outlines the proposed development at a city-regional scale.

Table 4-5: Proposed management actions for Kafue Flats regional water supply

Management Actions	Description	References
Irrigation	Existing irrigation: 35021 ha (I1) Short-term irrigation upgrade: 39971 (I2) Long term irrigation upgrade: 65971 (I3)	(The World Bank, 2010)
Hydropower	Kafue Gorge Upper: climate start-up year 1972 (H1) Kafue Gorge Lower: expected in 2022, modelled from 1972 historical climate year (H2)	(Bhattarai et al., 2010; Spalding-Fetcher et al., 2014)

Sugar is a major crop in the Kafue Flats and the largest irrigation scheme in Zambia is in the Kafue Flats. The irrigation expansion was based on the Multi Sector Investment Opportunities Analysis (MSIOA) study by the World Bank (The World Bank, 2010) which highlights identified irrigation projects and the maximum theoretical potential for irrigation. Using these future irrigation projections meant having an analysis of the irrigation area specific to the study area and the crop area for each of the proposed scenarios. Studies that have explored the expansion of land under irrigation within the Kafue Flats have found that they should happen in conjunction with a moderate expansion of hydropower infrastructure, and still expansion would be less than 40,000ha (World Bank, 2009; Chomba and Nkhata, 2016).

The existing hydropower dam releases from Itezhi-Tezhi to Kafue Gorge Upper help to limit the seasonal variability for sugar cane irrigation (Chomba and Nkhata, 2016). The hydropower development scenarios consider regional plans that have already been implemented or are in the process, namely Kafue Gorge Upper and Lower, as these were assumed to have minimal financial and technical barriers. It should be noted that Zambia sugar generates most of its own power, reducing its dependency on the supply from the Kafue Gorge Upper hydropower generation and its water footprint (WWF, 2017). The risk analysis looks at a combination of the management scenarios and the climate and socio-economic stressors; these are conceptually shown in **Table 4-6.** The basin-scale scenarios were based on the 2035 city-scale scenario as this was the most realistic decision-making time frame. By modelling basin-scale impacts in this way the assumption is that all the socio-economic stressors and management actions of the 2035 city-scale scenario have been implemented.

Table 4-6: Water demand management scenarios

Scale	Scenarios	Socio economic stressors	Climate stressors	Management actions
City	P1 (2017)	See figure 4.7	City-scale (Δ regional MAR and Δ regional MAP)	Infrastructure upgrades based on the Water Supply Investment Master Plan
	P2 (2020)			
	P3 (2035)			
Basin	P3H1 (2035 Baseline)	2035 socio-economic status of figure 4.7	Basin scale (Δ regional Temperature and Δ regional MAP)	City scale 2035 scenario including Kafue Gorge Upper
	P3H1I1 (2035)			Baseline and Existing irrigation
	P3H1I2 (2035)			Baseline and Short-term irrigation upgrade
	P3H1I3 (2035)			Baseline and Long-term irrigation upgrade
	P3H2I3 (2035 full development)			Kafue Gorge Lower and Long-term irrigation upgrade

4.5 Lusaka risk analysis and evaluation

Highlighting the opportunities and risks within Lusaka and the Kafue Flats is important for both public and private sector decision makers in the water management sector. The risks are both climate and socio-economically driven but the impacts of these risks require trade-offs. These risks can be investigated with the use of narratives which look at the nature and potential extent of these risks on a city and regional scale.

The management actions outlined in section were analysed using the city-regional WEAP model for the city of Lusaka and the Kafue Flats and the results are presented in this section. By quantifying the modelled vulnerabilities this section unpacks the identification of the climate and socio-economic stressors to a city-regional water system, and how the city-regional sensitivities and uncertainties translate into city-centric impacts on a water system. The basis for comparison in most cases was the modelled average from 1960-1990; assuming stationarity. A key assumption in the analysis is that the conditions upstream of the Kafue Flats and downstream of the development of the Kafue Gorge hydropower run-of river scheme will remain unchanged; n reality, this would not be the case but modelling climate and socio-economic areas outside of the study area was not within the scope of this research.

Risk definition

Decision-scaling uses the risk definition to inform decisions instead of identifying risks from climate projects. The risk definition (**Table 4-7**) show the level to which domestic and irrigation water demand are met, and the generation and reliability of hydropower; accounting for the water-energy-food nexus. The risk level could be due to climate or socio-economic stressors or a management scenario. Both high and sever risk should be considered unsustainable.

Table 4-7: Risk definition based on domestic and irrigation demand, and hydropower generation and reliability

Risk level	Average domestic water demand (incl. NRW)*	Average Irrigation demand	Total Hydropower generation	Hydropower reliability
Low risk	80%≤ of demand met	80%≤ of demand met	430 GWH/month≤ (based on average generation 1993-2012)	71.8%≤ (based on average generation 1960-1990)
Medium risk	75% of overall demand met	75% of overall demand met	408.5 GWH/month≤ (low risk -5%)	68.2%≤ (low risk -5%)
High Risk	65% of overall demand met*	65% of overall demand met	387 GWH/month≤ (low risk -10%)	64.6%≤ (low risk -10%)
Severe risk	<65% of overall demand met*	<65% of overall demand met	<387 GWH/month	<64.6%

*For the domestic demands, the risk brackets were based on the estimated per capita consumption figures for medium cost housing. According to the LWSSD (Gauff Ingenieure, 2013) the future per capita consumption is 150 l/c/d, assuming that the 180 l/c/d for urban domestic use (modelled as 270 l/c/d total demand to include industrial and commercial use) is the 80% assurance of supply, 150 l/c/d would be the 65% assurance of supply below which unmet demand becomes a severe risk.

To provide context on the risks associated with historical climate and climate variability, data from the Climate Research Unit (CRU) (Harris et al., 2014) was used. To show the impact of El Niño/ Southern Oscillation (ENSO) and La Niña years (see **Table 4-8**) the mean monthly deviation of precipitation and temperature were used and plotted on the risk map. The precipitation and temperature deviations were estimated as a mean relative to the climatic baseline (1961-1990). Historical climate Condron's are represented by 0% change in precipitation and 0°C change in temperature.

Table 4-8: El Niño and La Niña years based on mean monthly CRU values

Year	Temperature (°C)	Deviation (°C)	Precipitation (mm)	Deviation (%)
Historical 61-90	21.3		817	
Recent 14-15	22.7	1.4	671	-18%
ENSO 97-98	22.9	1.6	803	-2%
La Niña 10-12	22.8	1.5	878	+7%

For each risk map, precipitation variability is represented on the x-axis and the other climate variable (i.e. mean annual runoff variability or temperature) is represented on the y-axis. The risk map management scenario (**Table 4-6**) is shown in the map's bottom left-hand corner.

4.5.1 City-scale risks and responses

The city-scale risk map looked at the 2017, 2020 and 2035 total met domestic demand (inclusive on non-revenue water); and city-scale relevant climate variability (variations in runoff and precipitation). This scenario helped to identify that on a city-scale, the water system had no direct climate vulnerability and the vulnerabilities were related to the socio-economic stressors and city-scale management scenarios. **Figure 4-10** shows the risk map for three planning horizons, namely the 2017 baseline, the 2020 development and the medium-term plans for 2035. The maps consider the isolated city-scale climate change system stressors for water supply, the demographic and water use changes and the city scale socio-economic development for each respective planning horizon (P1, P2 and P3).

a. Lusaka: total demand met-including domestic NRW (%)

RUNOFF VARIATION (%)					
30	75%	75%	75%	75%	75%
20	75%	75%	75%	75%	75%
10	75%	75%	75%	75%	75%
0	75%	75%	75%	75%	75%
-10	75%	75%	75%	75%	75%
-20	75%	75%	75%	75%	75%
-30	75%	75%	75%	75%	75%
P1	-50	-25	0	25	50
2017	PRECIPITATION VARIATION (%)				

b. Lusaka: total demand met-including domestic NRW (%)

RUNOFF VARIATION (%)					
30	100%	100%	100%	100%	100%
20	100%	100%	100%	100%	100%
10	100%	100%	100%	100%	100%
0	100%	100%	100%	100%	100%
-10	100%	100%	100%	100%	100%
-20	100%	100%	100%	100%	100%
-30	100%	100%	100%	100%	100%
P3	-50	-25	0	25	50
2020	PRECIPITATION VARIATION (%)				

c. Lusaka: total demand met-including domestic NRW (%)

RUNOFF VARIATION (%)					
30	86%	86%	86%	86%	86%
20	86%	86%	86%	86%	86%
10	86%	86%	86%	86%	86%
0	86%	86%	86%	86%	86%
-10	86%	86%	86%	86%	86%
-20	86%	86%	86%	86%	86%
-30	86%	86%	86%	86%	86%
P3	-50	-25	0	25	50
2035	PRECIPITATION VARIATION (%)				

Figure 4-10: Risk map under (a)P1, (b)P2 and (c) P3 development

Under historical climate conditions, the baseline (P1) city-scale risk map shows a medium risk; meaning that the city-scale water system is currently vulnerable and unable to satisfy demand to achieve low risk. This supported the discussions held in the learning labs about infrastructure constraints being the primary vulnerability for the Lusaka water system. The P3 2035 management scenario was used as the baseline on which to develop the Kafue Flats city-regional scale management scenarios. The next section will elaborate on the vulnerabilities on a city-regional scale and for the water-energy-food nexus.

4.5.2 Regional-scale risks and responses

The city-regional scale risk maps accounted for climate variability at a regional-scale (variations in temperature and precipitation) and the proposed management scenarios for Kafue Flats regional water supply (see **Table 4-5**).

Baseline 2035 development

The baseline domestic 2035 development altered the risk status of the isolated city-scale model (**Figure 4-11a**). As an isolated city-scale model the domestic water demand met indicator (**Figure 4-10** c) was a low risk (86%), but within the city-regional model this risk marginally moves into the medium risk (79%) (**Figure 4-11a**). The demand met indicator varied negligibly over all the regional-scale management scenarios and remained constant at 79%, further confirming that infrastructure capacity constraints play a significant role in domestic water supply in Lusaka. The hydropower indicators relate to the Kafue gorge Upper reservoir. Overall the average monthly hydropower generation (**Figure 4-11b**) was mostly a low risk, except in the case of precipitation decreasing by 20%. Although the average monthly generation was low risk, the hydropower reliability (**Figure 4-11**c) indicates that low risk for increasing precipitation climate stressors and severe to medium risk for decreasing precipitation climate stressors. This is important to note as it highlights that although average generation is low risk, it represents both over generation and under generation, with the system not being reliable during the latter.

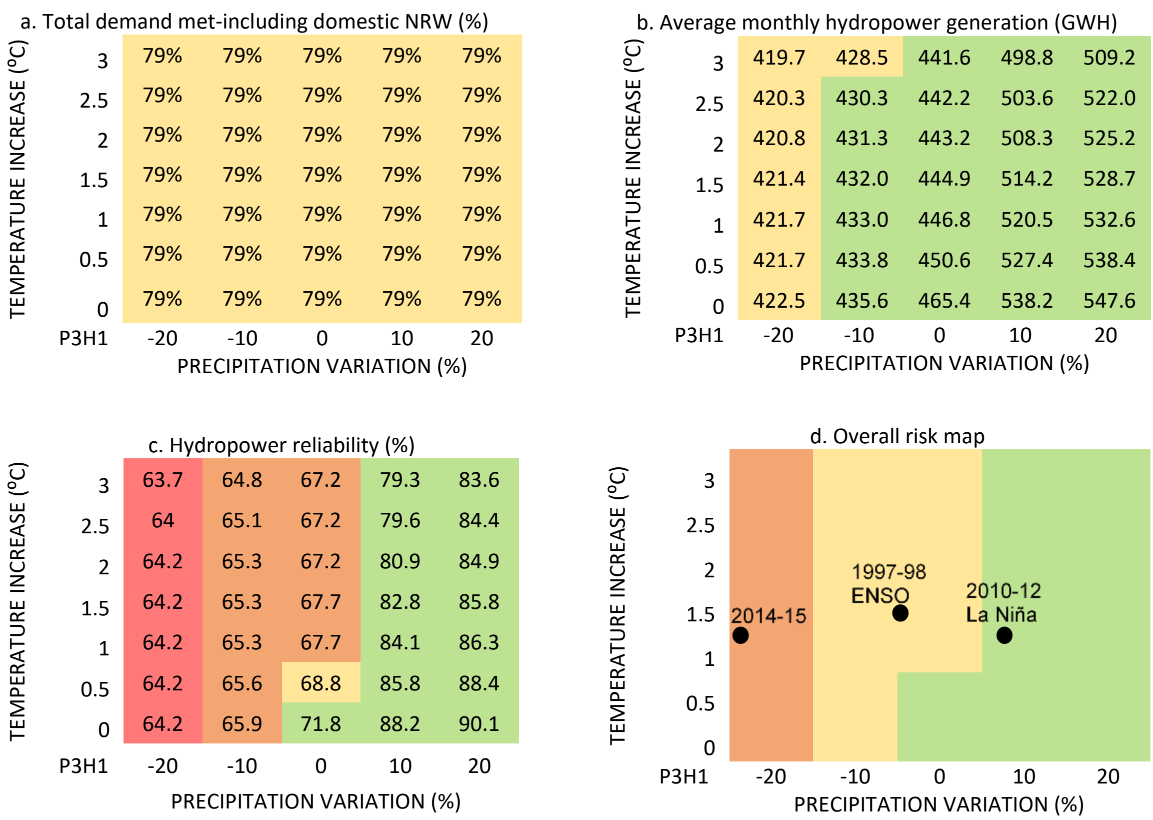

Figure 4-11: 2035 baseline (P3H1) development city-regional risk maps

The overall risk map for the P3H1 scenario (**Figure 4-11d**) shows that for the 2035 baseline development scenario the climate stressor which poses leaves the system most vulnerable is changes in precipitation. Increase have an overall positive effect, however the plotted recent climate averages for the 2014-2015 period show that the city has recently been at high risk. The

2014-2015 period was also during the most recent drought during which learning lab participants did refer to power shortages during that time.

Hydropower development

The modelled average baseline hydropower generation at Kafue Gorge Upper is 465.4GWh/month in comparison to the 1993-2012 monthly generation of 430 GWh (Spalding-Fetcher et al., 2014). The generation at Kafue Gorge Upper does not appear to be greatly affected by warmer and drier climates in terms of generation, but its reliability is impacted. The releases of Kafue Gorge Upper determine the generation at Kafue Gorge Lower which is a run-of-river scheme. The planned extension of Kafue Gorge Lower will increase the overall hydropower reliability (**Figure 4-12b**) in comparison to the baseline 2035 development P3H1. Because the hydropower development scenario is based on the full irrigation development scenario, the total irrigated demand met for sugarcane (**Figure 4-12c**) is the same as that for the P3H1I3 scenario (**Figure 4-15c**). The average monthly hydropower generation shown (**Figure 4-12a**) is only for Kafue Gorge Upper hydropower plant. Based on the overall risk map (**Figure 4-12d**) the additional hydropower plant at Kafue Gorge Lower does decrease the overall risk of the scenario in comparison to P3H1I3, on which it is based; the scenario is mostly medium to high risk.

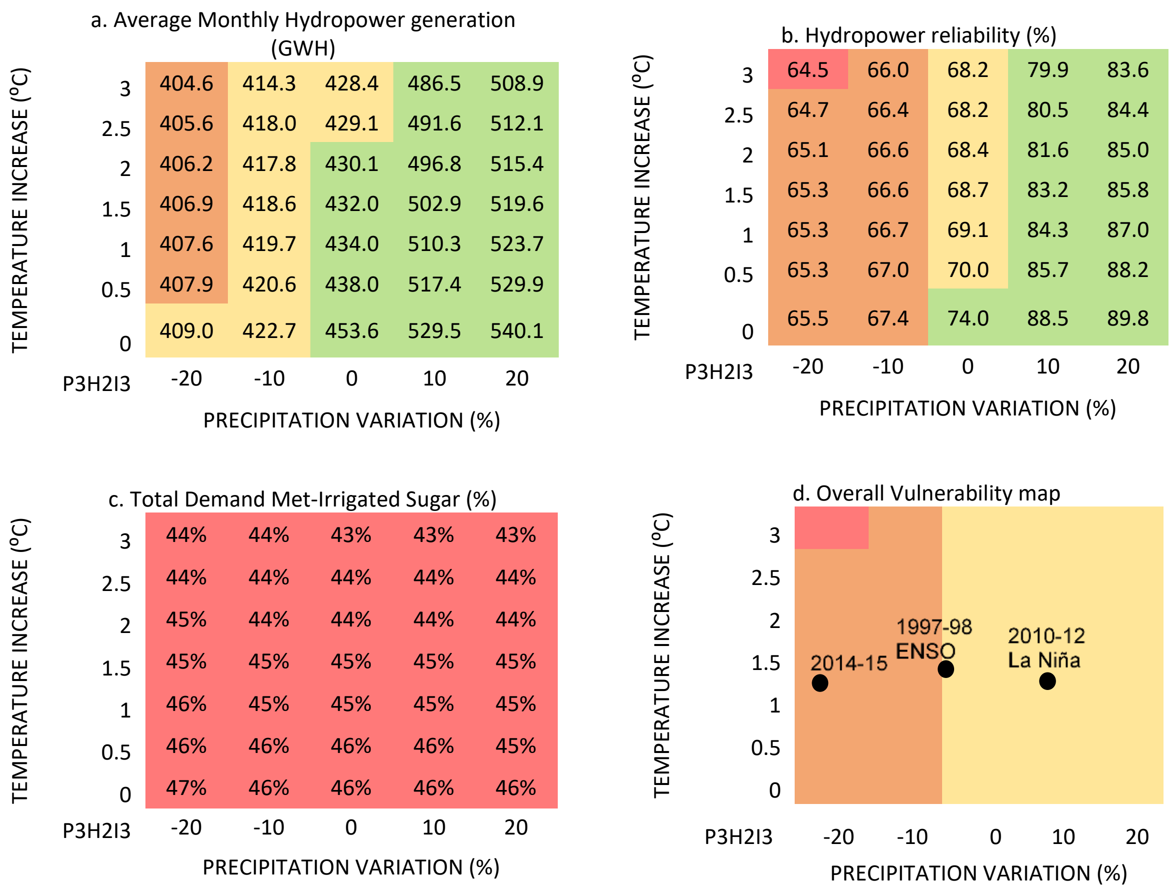

Figure 4-12: Full development (P3H2I3) scenario city-regional risk maps

Irrigation development

The impact of increasing irrigation area is that it increases the overall demand requirement from the Kafue river. In the case of the Kafue flats and the Kafue Gorge hydropower the change in irrigation area has minimal impact on the generation or the downstream discharge (Figure 4-13). Increasing irrigation reduced the average hydropower generation (Figure 4-13) but the reduction was negligible when comparing the same climate state across the irrigation scenarios. According to the WWF, the amount of irrigation water abstracted from the Kafue Flats exceeds the total permits for agricultural water use (WWF, 2017). This is important to note as although the risk maps for all the irrigation scenarios show a deficit in supply (**Figure 4-15**), there may be water abstraction that is unregistered.

Like the P3H1 baseline scenario, for the hydropower generation and reliability, precipitation variability has more of a risk impact than temperature variability. Similarly, the average monthly hydropower generation (**Figure 4-13**) shows less risk than that for hydropower reliability (**Figure 4-14**). The hydropower reliability plots also show that even with no changes in precipitation both the current day, and future irrigation scenarios present a high risk (between 69.9-70.4% reliability). In contrast to the hydropower indicators, the irrigation demand met indicator shows little risk variation for precipitation variability for all scenarios, this is partially due to the Kafue Flats abstraction constraint. Even if there is a precipitation shortfall, the abstraction constraint limited the amount of water available for irrigation. The irrigation demand met indicator is greatly influenced by changes in temperature, with increasing temperatures resulting in higher risk. This is to be expected as increasing temperature increases evapotranspiration.

The overall risk maps for the existing irrigation and the short-term development (**Figure 4-16**) show qualitatively similar levels of risk as the historical climate events (ENSO, La Niña and 2014-2015) plot within the same risk definition on both maps. This is due to the area increase between the two scenarios being relatively small. An area of concern is the P3H1I3 scenario risk map (**Figure 4-16c**), which does not show any climate future in which there is a low risk at the city-regional scale. this high risk is mostly due to the low level of irrigation demand being met (on average 46%, **Figure 4-15c**); however, the allocated abstraction for irrigation may not be capped at the existing capacity in which case there is potential for this risk level to decrease. Information on the future allocation for the increased irrigation area was not available at the time of this study.

The vulnerabilities and risk for the water supply of Lusaka will be further discussed in chapter 5.

a. Average Monthly Hydropower generation (GWH)

TEMPERATURE INCREASE (°C)					
3	405.9	416.0	429.8	487.7	509.2
2.5	407.3	418.0	430.5	492.6	512.4
2	407.9	419.3	431.5	497.6	515.7
1.5	408.6	420.0	433.4	503.6	519.7
1	409.3	421.1	435.3	510.4	523.8
0.5	409.5	422.1	439.3	517.8	530.0
0	410.5	424.1	454.7	529.7	540.1
P3H1I1	-20	-10	0	10	20

PRECIPITATION VARIATION (%)

b. Average Monthly Hydropower generation (GWH)

TEMPERATURE INCREASE (°C)					
3	405.9	415.6	429.4	487.4	509.1
2.5	406.9	417.6	430.1	492.3	512.3
2	407.5	418.9	431.2	497.4	515.6
1.5	408.2	419.7	433.0	503.4	519.7
1	408.8	420.7	435.0	510.2	523.8
0.5	409.1	421.7	438.9	517.7	530.0
0	410.1	423.7	454.4	529.6	540.1
P3H1I2	-20	-10	0	10	20

PRECIPITATION VARIATION (%)

c. Average Monthly Hydropower generation (GWH)

TEMPERATURE INCREASE (°C)					
3	404.6	414.3	428.4	486.5	508.9
2.5	405.6	416.4	429.1	491.6	512.1
2	406.2	417.8	430.1	496.8	515.4
1.5	406.9	418.6	432.0	502.9	519.6
1	407.6	419.7	434.0	509.8	523.7
0.5	407.9	420.6	438.0	517.4	529.9
0	408.9	422.6	453.6	529.5	540.1
P3H1I3	-20	-10	0	10	20

PRECIPITATION VARIATION (%)

Figure 4-13: Average monthly hydropower generation (GWH) under I1, I2 and I3

a. Hydropower reliability (%)

TEMPERATURE INCREASE (°C)					
3	62.1	63.2	65.6	77.4	81.7
2.5	62.1	63.4	65.6	78.2	83.1
2	62.6	63.7	65.6	79.6	83.3
1.5	62.6	63.7	66.1	81.5	84.1
1	62.6	63.7	66.4	82.3	84.9
0.5	62.6	64	67.5	83.9	86.6
0	62.9	64.5	70.4	86.3	88.7
P3H1I1	-20	-10	0	10	20

PRECIPITATION VARIATION (%)

b. Hydropower reliability (%)

TEMPERATURE INCREASE (°C)					
3	62.1	63.2	65.6	77.4	81.7
2.5	62.1	63.4	65.6	78.2	83.1
2	62.6	63.7	65.6	79.6	83.3
1.5	62.6	63.7	66.1	81.5	83.9
1	62.6	63.7	66.1	82.3	84.9
0.5	62.6	64	67.5	83.9	86.6
0	62.9	64.5	70.4	86.3	88.7
P3H1I2	-20	-10	0	10	20

PRECIPITATION VARIATION (%)

c. Hydropower reliability (%)

TEMPERATURE INCREASE (°C)					
3	61.8	63.2	65.6	77.4	81.7
2.5	61.8	63.4	65.6	78.2	82.5
2	62.4	63.7	65.6	79.3	83.3
1.5	62.6	63.7	66.1	81.2	83.9
1	62.6	63.7	66.1	82.3	84.9
0.5	62.6	64	67.2	83.9	86.6
0	62.9	64.5	69.9	86.3	88.7
P3H1I3	-20	-10	0	10	20

PRECIPITATION VARIATION (%)

Figure 4-14: Hydropower reliability (%) under I1, I2 and I3

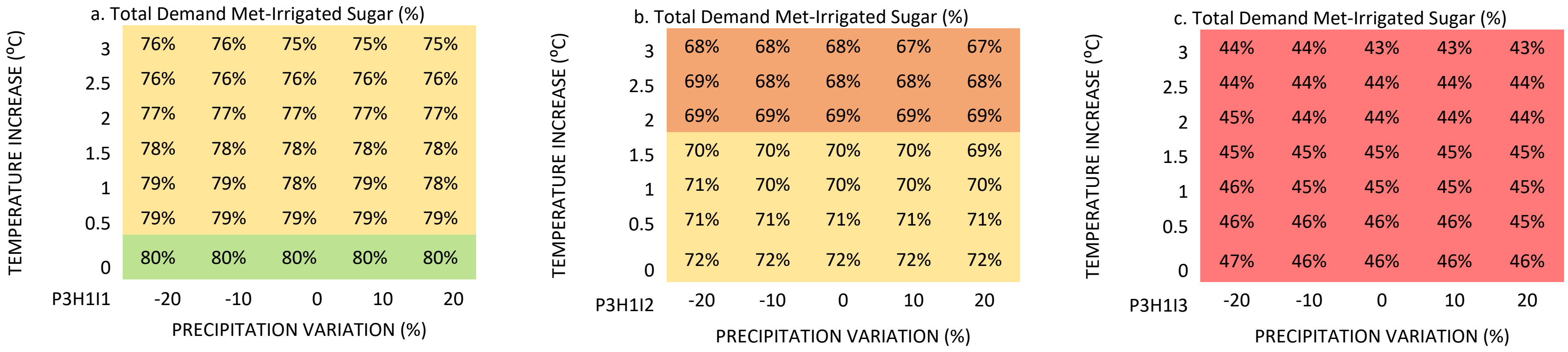

Figure 4-15: Total irrigation demand met (%) under I1, I2 and I3

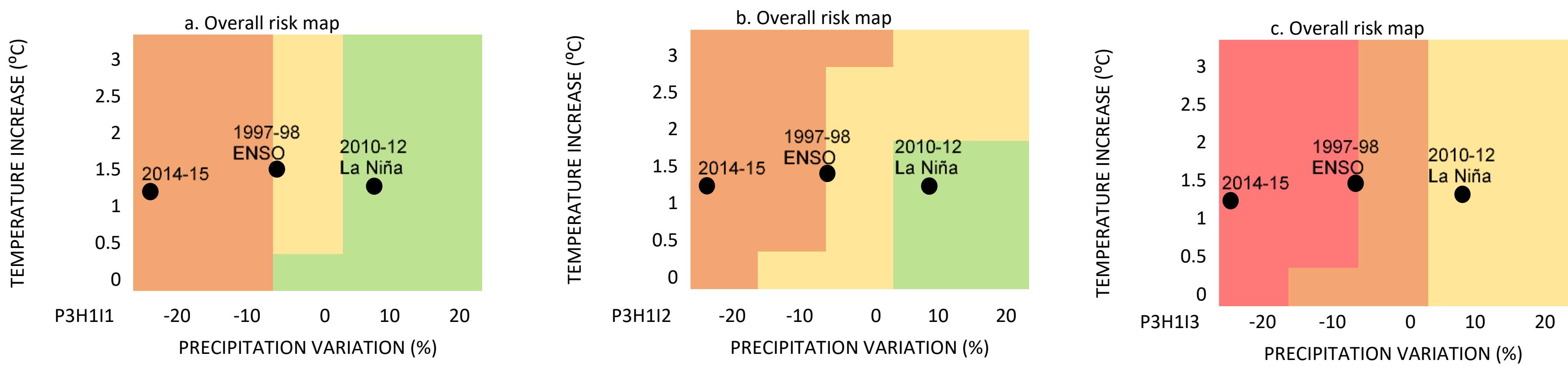

Figure 4-16: Overall risk map for irrigation scenario

5 DISCUSSION

5.1 Benefits of adaptive decision support frameworks

The use of the decision-scaling framework, and other bottom-up adaptive decision-support frameworks, is that they have the potential to lead to a better understanding of the challenges, opportunities, and trade-offs of good water governance. Makes best use of the available information and manages uncertainties. Key lessons learned in the application of decision scaling for adaptation decision support were:

The role and representation of stakeholders: the first step of stakeholder engagement is critical to approach taken to find the system risks. in the case of Lusaka, the project framework developed for FRACTAL looked to engage with sectors in which climate information plays a role. This project condition spoke to those in the water sector and the representation from water sector institutions was evident in the learning labs (see **Appendix C**). However, cross-sectoral representation (e.g. from the agriculture and energy sector) would have also been valuable to unpack the system complexities early-on in the decision-scaling process. The capacity of the learning lab participant stakeholders to implement change in their respective institutions is also limited.

The process brought to the foreground the sectors that should be communicating for urban water security in Lusaka, and some of these engagements will be further supported through LuWSI. Because the process was iterative and required feedback from the learning lab participants, ensuring that stakeholders present could further inform and explain the actual system versus the perceived system was valuable. Having transdisciplinary stakeholders allowed for the engagement and risk identification to not always be technically focussed but also highlight economic and environmental risks as well. The value of co-production is that it allows for input from stakeholders to develop information that is useful and user-friendly.

Identifying the key method output: the methodology followed in this study produced a model output which could be further developed by stakeholders to integrate additional sectors and change the modelled management actions and assumptions. However, the model produced is not the primary benefit of the application of bottom-up adaptation decision-support. A lesson learned is that the benefits of such an approach are firstly the engagement with stakeholders and between stakeholders from different institutions. Having input from those who manage and operate within city systems, provides insight into the system complexities that top-down approaches do not offer. It produces informed and realistic assumptions and encourages stakeholders to engage with both climate and non-climate impacts. The dialogue itself is beneficial as it allows stakeholders to have a new frame of thinking in which they understand the importance of operating outside of silos.

City-complexities and trade-offs: taking a city-scale approach to urban water security unpacks the complexities that are relevant at a city-scale, which can sometimes not be identified at a national or basin-scale. By isolating the city vulnerabilities, the method allowed identification of city-scale measures to resilience that will be vital in achieving regional or national resilience, for example the peri-urban distribution and infrastructure capacity constraints. Application of the bottom-up approach also helped to highlight where trade-offs existed at a city-scale and at a city-regional scale. These trade-offs were between institutions, proposed development, and supply options. A key lesson learned regarding city-complexities is that expected system stressors, such as climate change may not always have direct impacts that translate into vulnerabilities, in the case of this study, the climate stressors created indirect vulnerabilities at a city-regional scale that translated to city-scale impacts.

5.2 City-regional system vulnerabilities

In an African context, the situation of water in the Kafue Flats is not unique in that it brings together an array of sectors and institutions. Therefore, water allocation and sector planning cannot be carried out in silos, as maximization of water use by any one sector will have negative impacts on both a city and regional scale. The risks of water not being adequately managed are shared between the sectors. Allocating the same priority to domestic, irrigation, and hydropower demand allowed for analysis of where there may be trade-offs between these water dependent sectors. The city-regional water system of Lusaka and the Kafue Flats had vulnerabilities to both socio-economic and climate changes.

5.2.1 Climate change vulnerabilities

Choices: the climate stressors chosen for both the city and the city-regional model were important in determining the system vulnerabilities. Within the scope of this study, at a city scale, Lusaka's water supply is vulnerable to climate based on the quantity of water available for abstraction (i.e. Kafue river Mean Annual Runoff) and the quantity of precipitation available for groundwater recharge (i.e. regional Mean Annual precipitation). Because groundwater recharge was proportionate to changes in precipitation, variations to mean annual runoff were thought to have a significant impact on the water security for Lusaka.

At a city-regional scale, the climate stressors of variations in Mean Annual Precipitation and Temperature were well suited to simulating vulnerabilities for water availability for domestic, agricultural and energy use. However, because these variations were based on historical monthly averages they did not explicitly account for climate extremes such as floods and droughts, which would hydrologically and economically negatively impact the water (e.g. loss of infrastructure, health hazards), energy (e.g. limited production during drought), and food (e.g. decrease yields during droughts and crop loss during floods) nexus.

Consequences: the climate change responses are predominantly evident at a city-scale.

Figure 5-1 shows that the consumptive allocation is a negligible proportion of the minimal operational flow between Itezhi-Tezhi reservoir and Kafue Gorge Upper. This made the city-scale system not have any vulnerabilities to climate stressors. to any predicted climate variation. At a city-scale, this lack of climate vulnerability puts the city in a flexible space.

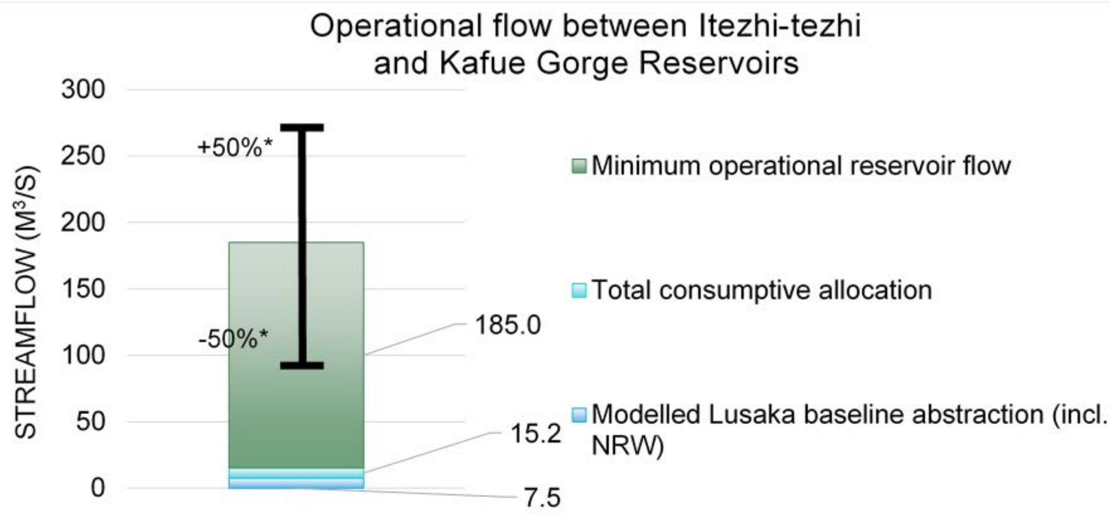

Figure 5-1: Operational flow between Kafue reservoirs showing consumptive allocation (Gauff Ingenieure, 2013)

Lusaka abstraction and *Predicted range of changes in runoff for the Kafue River (Fant, Gebretsadik and Strzepek, 2013)

At a city-regional scale, the hydropower indicators (for generation and reliability) were mostly vulnerable to changes in precipitation, while the irrigation indicator (for water demand being met) was mostly vulnerable to temperature variation. The stepwise changes in the overall risk maps (figure) show how the two parameters of temperature and precipitation need to be holistically considered in the water dependent sectors.

Connections: the climate change responses for the city and the city-regional system are being considered in isolation. There is a connection between Mean Annual Runoff and precipitation and temperature, but this was not modelled. At both a city and city-regional scale, this would have connected the two systems as the vulnerabilities could be viewed on the same set of axes. There is also a connection with the temporal scale at which the climate stressors are varied. The choice to model monthly excludes daily extreme events which could have greater consequences. Most importantly for climate change responses is the model input. This study used an already calibrated ZDSS model, however changing the climate input may have produced different risk maps.

Uncertainties: most climate projections are for the year 2040 and beyond creating climate uncertainty for the short-to medium term, which is the temporal focus of this study. There is also a lack of data around climate impacts to groundwater, which at a city-scale is important for water security for Lusaka and the impacts of climate on the Kafue Flats wetlands, which is important at a city-regional scale, for water supply and energy and food production. Existing climate projections could be mapped on the risk maps, to determine the predicted risk, but the modelled variation range may be too broad (i.e. large variation increments) to effectively distinguish between the different predictions. The study scope also did not include the impacts of climate variations upstream of Itezhi-Tezhi, which would also translate to regional-scale and city-scale impacts.

5.2.2 Socio-economic change vulnerabilities

Choices: the socio-economic change choices were linked to the existing development plans as outlined in the case study. Each of the choices at both either a city or a city-regional scale affected the vulnerability of the water system and would have financing impacts and associated timelines. They are summarised below

- **Population**: the choice to change population at a city-scale was a primary consideration as African cities are expected to grow considerably by 2050 (Eckart et al., 2011). This change determines the demand requirement at a city-scale which would impact the need for infrastructure to meet that demand. At a city-regional scale changes to population would also affect the energy requirement from hydropower, the amount of land available for agriculture as communities expand onto fertile land, and the agricultural yield requirements as Lusaka is a key export for the Kafue Flats (WWF, 2017).
- **Non-revenue water (NRW)**: the choice to include NRW as a socio-economic change is that it a loss of water that could have otherwise been used elsewhere. This change was only applied at a city-scale, as it is at this scale that it was considered to have the greatest impact on water security. Non-revenue water would be applicable for both irrigation and hydropower at a city-regional scale too but were not applied (Millennium Challenge Corporation, 2011).
- **Peri-urban population distribution**: for future development, management scenarios consider the decrease in the peri-urban population, the choice to use this as a city-scale socio-economic indicator was that it showed a variation in demand and was an indicator of development i.e. a smaller population with "peri-urban level" access to water, means more of the population is being served through individual connections. NWASCO (2014) considers water kiosks, a key form of water supply in peri-urban areas, a stop-gap measure in water supply.
- **Water supply infrastructure**: the choice to use water supply infrastructure as a socio-economic change is that increasing a population's water supply is linked to improved health

and social wellbeing (Eckart et al., 2011). At a city-scale this included expansion of both surface water and groundwater abstraction; there is agreement on development of both these options as they are outlined in the Water Investment Master Plan (Millennium Challenge Corporation, 2011). These are long term projects which play a vital role in the city-scale water-security.

- **Irrigation expansion**: there are three development options for irrigation that were the choice for the socio-economic changes. These were determined through a literature review and represent current, short term and optimal sugar cane irrigation. The availability of water for the irrigation node, although influenced by climate is also greatly influenced by the allocated abstraction. Without an increased allocation the irrigation supply will not be met or will be illegally abstracted, hence the sever risk for optimal irrigation development. This choice was limited to sugarcane irrigation and excluded other irrigation in the study area, which could also affect water security.
- **Hydropower development**: although Zambia's hydropower is distributed via central grid, meaning that the energy produced at Kafue Gorge Lower is not necessarily that which would supply the city of Lusaka, the hydropower generated in this region does contribute approximately 50% of Zambia's energy, making its overall production a key factor to consider for water supply and economic development

Consequences: the socio-economic changes pose a risk to the water security of Lusaka. There are both costs and benefits of these changes. At a city-scale the benefits are evident in that increased infrastructure can handle the increased demand, although this is based on 15% NRW by 2035 (further discussed under uncertainties). City-regional benefits are that increased hydropower production, decreases the water security risk at a city-scale. Overarching costs of at a city-regional scale are the potential water pollution and over abstraction associated with increased irrigation; and that an increased population would increase their footprint on the existing groundwater aquifer which would have impacts to groundwater recharge and quality at a city-scale.

Connections: at both a city and a city-regional scale there are connections between the different socio-economic changes both spatially and temporally. Each of these changes will affect how stakeholders engage with the water resource-as there is more abstraction, the governance of the resource- as institutions should work together for implementation and have an impact on the environment in the short and the long term. Some of these effects are evident in the consequences above. The success of some of these changes is dependent on the success of another. For example, without sufficient hydropower, the water supply infrastructure at a city-scale cannot be expanded; without decreasing the non-revenue water, the new infrastructure will still be unable to meet demand; and without the adequate infrastructure for supply the peri-urban regions may not be able to move away from more "informal" supply methods such as kiosks, thus keeping their demand low. Despite these interconnections, there is still a tendency for some of the sectors to work in silos which inhibits building resilience (Kavonic et al., 2017).

Uncertainties: the uncertainties for these social-economic changes include, developing realistic timelines and whether these changes will still solve future water security issues in a changing environment. Some of these changes, such as infrastructure development, are on the critical path for future development. The other uncertainties are linked to governance and urban water management as they are dependent on the different sectors working together and collecting data from one another. The various stakeholders will need to jointly decide on priority areas, for which water security, specifically at an urban scale, may not be a priority area. Another uncertainty is that the current trends for development do not show some of these socio-economic changes as being on track. For example, the change in the peri-urban distribution has not yet dropped to 50%, nor has the NRW dropped to 30%, and it's nearly 2020 (NWASCO, 2017). This would influence the city-scale water demand and priority supply infrastructure.

5.2.3 Water co-dependencies (water-energy-food nexus)

Although the allocated consumption for the Kafue Flats is relatively low in comparison to the overall streamflow, at a city-scale, trade-offs still exist for the water dependent sectors. Climate and socio-economic changes will need the water dependent sectors to have an agreement on how best to manage and make decisions about the Kafue Flats water resources. In the case of hydropower, the potential future impacts of climate change should be considered in the decision making and planning process; especially when accounting for future plants such as the Kafue Gorge Lower where investments may depend on the hydropower reliability and generation. The increased power demand will mean an increased water demand, however increasing use from economic development would mean less water is available for hydropower generation; or the converse that ensuring water availability for hydropower generation would restrict the availability of water for economic development.

Within the water-energy-food nexus the primary system vulnerability was the availability of water to sustain the energy-sector as this would ultimately determine the availability of energy to supply water to the city of Lusaka. According to LWSC's energy consumption data, the boreholes consume about 0.4 kWh/m^3, whilst water pumped from Kafue consumes about 1.9 kWh/m^3 (Millennium Challenge Corporation, 2011, p. 67). Under historical hydropower generation (430 GWH per month) for Kafue Gorge Upper, the current municipal pumping (SW: 95,000m^3/day and GW 130,000m^3/day) uses approximately 2% of the hydropower generation. However, **Figure 5-2a** shows that in the baseline scenario P3H1, hydropower generation is less than 430GWH/month for 66% of the climate stressed combinations.

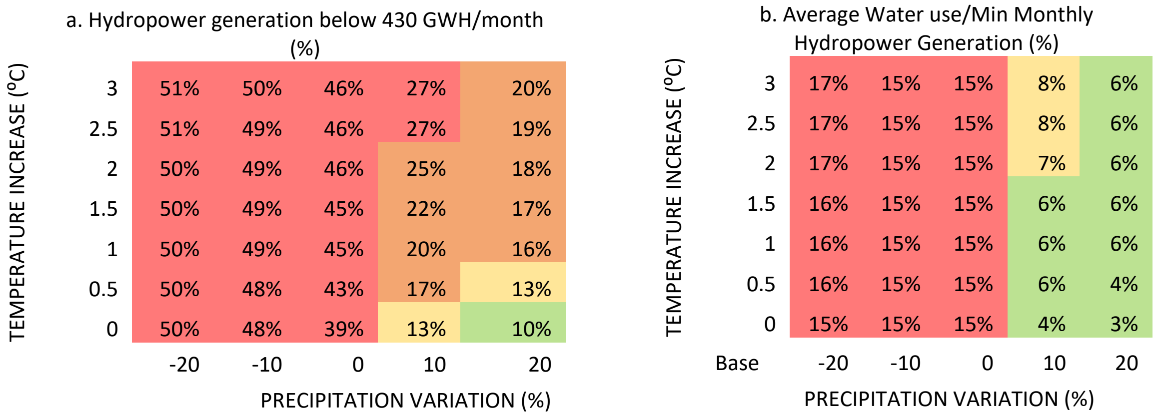

Figure 5-2: P3H1 risk map for (a) average monthly hydropower generation below 430GWH, and (b) average daily pumping power consumption as a percent of minimum daily hydropower generation

When considering the simulated minimum daily hydropower generation, **Figure 5-2b** shows how the consumption for pumping water for domestic supply can use up to 17% of hydropower generation under severe risk climate stressors (i.e. decrease in average precipitation and increase in average temperature). This further highlights the importance of city-regional impacts as at a regional-scale, water is needed for to generate energy, but at a city-scale, energy is needed to supply water. Although these city-scale energy constraints, and the energy constraints on the agriculture sector were not explicitly modelled, these trade-offs are important to note.

Another trade-off for water security to Lusaka within the city-regional system is with the allocation for irrigation. Maintaining the increasing irrigation poses a greater risk to water supply as abstraction permits will need to be increased to reduce the risk for the irrigation demand being met indicator. City-scale water security impacts of increased irrigation are also likely to take the form of water resource pollution as nutrient-rich effluents are often discharged back into the Kafue river system (Uhlendahl et al., 2011). Effluent-rich water would also increase the growth of aquatic weeds which pose a risk to hydropower production, which would then pose a risk to city-scale water supply. Water quality was outside the scope of this study and an assumption was that all water resources were of an adequate level of quality but on a city-regional scale, effluent discharge from agriculture would increase the risk to water security. On a city-scale, the location of water sources in relation to polluting sources such as pit latrines and solid waste would also greatly increase the risk to water security.

The Kafue Flats is important for sustaining the agriculture industry: the agriculture sector, if expanded, offers significant opportunities for economic growth both within the Kafue Flats and in Zambia. Further cultivation will support smallholder farmers, create additional employment, and increase food security (WWF, 2017). The reduction of agriculture production will create vulnerabilities for the livelihoods of those in the Kafue Flats agriculture sector. A decrease in the allocated water, or its variability due to stressors, will influence agricultural productivity. Area expansion for cultivation may also be limited by the reliability and pricing for power, as the current power supply is mostly for industrial and domestic use.

Hydropower is heavily intertwined in the water sector of the Kafue Flats: as most of Zambia's energy production is from hydropower, the streamflow volume and regime within the Kafue flats is important. Kafue Gorge Upper dam is designed to contribute approximately 45% of Zambia's electricity. The operating rules for the dam have been developed such that the ecology of the Kafue Flats can be maintained, however there is room for these rules to be improved. When power production drops , it impacts the ability of water providers to supply water, as their operation is affected, but it also leads to the use of biomass such as wood or charcoal, which can negatively affect the local environment (Pegasys and WWF, 2016). Environmental changes in the Kafue flats e.g. siltation also have detrimental impacts for the generation of hydropower. The existing national power deficit means that although regionally sufficient power exists to supply Lusaka within the Kafue Flats, re-distribution may pose risks to urban development.

5.3 Lusaka water security: challenges and chances for resilience

There are many future uncertainties for which resilience is the key to adaptation as it manages risks and builds capacity to cope with events that are unpredictable (UN-Water, 2010). The application of immediate adaptation is preparation for the future, using context specific measures to build resilience. Management of water resource systems also affect the socio-economy which makes water-related adaptation pivotal to achieving sustainable development (UN-Water, 2010, p. 11). Sustainable adaptation will require the integration of infrastructure, policy and changes to behaviour.

The world bank identifies Lusaka as a city that should be considering IUWM as it sits in a quadrant with cities that face high water-related challenges and have a high capacity (The World Bank, 2012, p.43). There are several emerging water security challenges and chances for resilience in cities. If the development of cities is to be resilient and efficient the connections between resource management, urban planning and service delivery need to be recognised (Closas, Schuring and Rodriguez, 2012, p.2). The challenges and chances for urban water resilience will be discussed under the three levels of resilience: socio-economic, external hazard and socio-ecological resilience (Johannessen and Wamsler, 2017).

5.3.1 Socio-economic resilience

The is a challenges or a chances for socio-economic resilience are based on the capacity of the stakeholders and relevant institutions to initiate sustainable developments and the level of governance that dives the urban water services (Johannessen and Wamsler, 2017).

Financial support

Climate and socio-economic changes could add to the overall cost of urban water resource management, which in some ways is already underfunded (Muller, 2007, p.108). In developing countries, increased costs for adaptation to climate change will limit their ability to sustain themselves and protect the most vulnerable. The challenge with adaptation investments is distinguishing them from development investments and ensuring that investments are “climate proofed” (Muller, 2007, p.109). Insufficient financing will lead to water utilities operating with aging infrastructure which, in sub-Saharan Africa, increases the non-revenue water (Closas, Schuring and Rodriguez, 2012, p.3).

Financial sustainability was not within the scope of this research but is a challenge to water security as developing access to water resources needs financial resources. Without financing water security will only be temporary. In the case of Lusaka and the LWSC, collection efficiency is only 77% (NWASCO, 2017, p.91), which leads to situations where the LWSC cannot expand its services to the peri-urban areas and has limited supply reliability, average 17 hours per day (NWASCO, 2017, p.91). This results in the under-serviced areas, which are usually poorer areas, having to pay more for water supply alternatives and often at a lower quality; this is not unique to Lusaka and is evident in other African cities (Uhlendahl et al., 2011, p.9). An opportunity exists if water utilities know where their vulnerabilities are, and the associated risks, they may have increased eligibility for funding, either through official development assistance or private-sector investment (Uhlendahl et al., 2011).

One of the key components required for sustaining the economic growth of Africa is the rapid upgrading of the infrastructure in the region (Awadalla et al., 2012). According to Awadalla et al. (2012), approximately US$93 billion will need to be invested into the infrastructure gap for Africa over the next decade. The investment will go majorly towards long-term infrastructure which should have the capacity to deliver services under present and future climate and socio-economic conditions.

Institutional capacity

Financing adaptation leads to the associated institutional challenges. Institutions need to manage demand and realise that there a multiple holistic approaches to building resilience (Muller, 2007, p.109). Water and adaptation related institutions need to engage with communities and water-dependent sectors to identify and apply the optimal mechanisms, by mainstreaming adaptation into national development plans, IWRM is a way to achieve this (Muller, 2007, p.109).

A lack of coordination, and institutions being fragmented will slow down the implementation of policy, and will create undefined mandates making it difficult to enforce existing regulations that support the management of water resources (Closas, Schuring and Rodriguez, 2012, p.3). An argument can also be made for whether the power to manage water resources should be centralized or decentralized (Uhlendahl et al., 2011). Many water management systems in African cities still take a top-down approach (Uhlendahl et al., 2011) , however this study shows how a bottom-up approach can be holistic, include key stakeholders, and highlight the importance of bringing together different sectors. Lusaka has valuable policies and institutional frameworks which focus on water or are water dependent (see **Appendix A**), an opportunity exists to advocate for policy that focuses on IUWM.

The trade-offs between the water co-dependent sectors of energy and food within Lusaka and the Kafue Flats calls for effective water governance. This governance should look at the socio-economic and institutional frameworks (see **Appendix A**) that currently exist to support integrated urban water resource management. With the formation of LuWSI there is increasing cooperation in the Lusaka region to maintain water security, but this does not necessarily mean that operation is coordinated between the water dependent sectors such as agriculture and hydropower. The complexities of this coordination could be more complex in the future. Linking the decision making of the water-energy and food sector would provide a better understanding of the existing trade-offs and the cost of climate and socio-economic changes.

Information sharing

A resource that limits the decision-making process is the availability of data, the lack of critical climate and socio-economic information creates a gap between what needs to be known to make an informed decision and what is currently known. There are numerous water resource models that exist for this region of Africa, specifically looking at the Zambezi river (The World Bank, 2010; Pöyry Energy GmbH and Kling, 2011; Spalding-Fecher et al., 2016), however they often do not account for the impacts of climate and socio-economic changes at a city-scale as they tend to apply top-down approaches. These existing models, as applied in this study, are a useful starting point when evaluating a water system as they are already calibrated. They also give an overview of water management at a basin scale and how trade-offs between water dependent sectors are managed. There exists limited information about the groundwater resources for Lusaka. As these currently represent more than 50% of the city's water resources, this information gap poses limitations to the decision-making process, as decisions are uninformed. This was represented in the case study by putting an abstraction limit on the private boreholes, but this would not be the case.

5.3.2 Hazard resilience

The challenges and chances for hazard resilience are based on awareness of the climate change and environmental risks and identifying the existing trade-offs or win-wins in daily water supply (Johannessen and Wamsler, 2017).

Environmental management

Over abstraction of surface and groundwater resources poses a threat to sustainability. Pollution of these resources can also affect entire ecosystems sometimes worsened by poorly managed wastewater and solid waste removal. Expanding urban areas will also be environmentally affected by climate change and the increased unpredictability of extreme weather events (Closas, Schuring and Rodriguez, 2012, p.2). Water is the second most important natural resource in Zambia, after copper, and is core to the country's growth. Development in the energy sector will pose a risk to the environment as it reduces the available land for crop production and may cause a decline in habitat loss (Uhlendahl et al., 2011). This study did not consider the required environmental flows required to maintain the Kafue Flats, but this is an opportunity for development in the study area to ensure that the surrounding ecosystem is maintained.

Climate change considerations

Climate change will also pose a risk to the quantity and quality of water in Lusaka, specifically at a city-regional scale, this may pose a seasonal risk as the water system goes through hydrologic and environmental changes. The effects of climate change on water resources will vary regionally and will be dependent on a range of factors including; conditions of the availability of water, demographic changes, existing supply and demand, legal and institutional frameworks for water management and the resilience of the systems (UNU-INWEH, 2013, p.16). Most climate change will affect the water cycle and result in increased hydrological variability. Ways need to be found to cope with the expected changes such that water resources and services will be more resilient to coping with new conditions (UN-Water, 2010, p.2).

At a city-scale climate scale does not pose any direct risks but resilience will be required to deal with indirect risks such as population migration and health impacts as both wetter and drier conditions will impact the health sector. At a city-regional scale, resilience will mean being able to supply water in case of climate related energy shortages. Irrigation water requirements will also be impacted by increasing temperatures, affecting crop yields, growing seasons and the availability of water for abstraction; measures should be put in place to minimise these risks. for energy production, infrastructure should be able to manage the impacts of changing streamflow patterns, and alternate sources of environmentally friendly energy sources should be considered. Consideration should also be given to no regret measures, that will prove worthwhile doing even if no (further) climate change will occur.

5.3.3 Social-ecological resilience

The challenges and chances for socio-ecological resilience are based on integrated formal and informal urban planning which is driven by urbanization, and the cross-sector coordination for better management of infrastructure development (Johannessen and Wamsler, 2017).

Infrastructure development

The practical challenges to building urban resilience that are facing water managers include the quality of available climate, socio-economic and hydrological information (Muller, 2007, p.110). Little priority has been attached to the collection and processing of data required for water resource management over recent decades, thus there is limited information available to support planning and development (Muller, 2007, p.110). Delays in implementing water monitoring infrastructure will leave urban communities more vulnerable as design standards may no longer be applicable (Muller, 2007, p.110).

Existing water supply services in African cities are challenged by poor maintenance and operations that are inefficient (Eckart et al., 2011). In Lusaka this was evident by the vulnerability of the city-scale system to changes in non-revenue water and infrastructure development. The disparity between the planned development and the actual development to date, is a key challenge in the city of Lusaka; but an opportunity exists to ensure that the new developments are resilient to the primary risks such as energy shortages and water pollution.

Social equity

By 2030, there will be more urban population than rural in Africa, both urbanization and population growth will increase the risk for water security in African cities (Uhlendahl et al., 2011). Populations are expanding rapidly and their demand is greater than the capacity and/ or availability for supply in many urban contexts, thus increasing the risk of water scarcity (Closas, Schuring and Rodriguez, 2012, p.2). The current and future availability of water is affected by competing water uses as well as the urban sprawl that affects the catchment hydrology.

Part of the solution to achieving water security is ensuring that a discourse exists with communities and that public participation is established (Uhlendahl et al., 2011). Within these engagements it is important to be aware of the stakeholders in the room, the power plays that exist between them, and who would have the capacity and the mandate to implement recommendations to achieving security. A key social challenge is that although the study used the planned socio-economic changes as stressors for water security, the current progress of these changes is not yet on track. The stakeholder participation process of co-production applied in the study built on local knowledge and helped to build awareness and develop ways of communicating water system vulnerabilities in an accessible way.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Bottom-up adaptive decision-support, such as decision-scaling, are valuable in identifying city-centric vulnerabilities to inform decision making for water security. Three main problems were identified that this research could address, namely: water security for sustaining urban livelihoods, adaptation in decision-making and decision-support, and resilient city-centric water systems. The research investigated a bottom-up city-centric approach to adaptive decision-support through a case study of the application of decision-scaling for the water system of the city of Lusaka, Zambia.

The literature reviewed existing water systems, their security and how they are managed. Management reviewed included that for water dependent sectors, specifically the water-energy-food nexus and how these water systems are impacted by climate and socio-economic changes. The literature reviewed water in cities, specifically in Africa, and the adaptation required to ensure that the water systems are resilient to climate and socio-economic changes. The use of decision-scaling as a bottom-up adaptation approaches, was reviewed to find how the decision-support framework included stakeholder engagement, developing a systems model using WEAP, stress testing the system, and evaluating challenges and chances for resilience.

The application of decision-scaling was useful for identifying system vulnerabilities and unpacking the system complexities, co-dependencies and trade-offs; at a city-scale and a city-regional scale. The research informed decision-support African urban water system resilience to climate and socio-economic system stressors through a case study of Lusaka, Zambia. In the case of Lusaka, Zambia as dependent city of the Kafue Flats sub-basin there were city-scale and city-regional scale vulnerabilities to climate and socio-economic changes respectively. For the city-centric water system of Lusaka socio-economic changes increased the risk to water security, however at a city-regional scale climate changes created more system vulnerabilities, especially to the water dependent sectors of hydropower and agriculture and increased the system's risk.

The city-scale and city-regional scale systems were co-dependent and could not investigated in silos as city-regional vulnerabilities translated to a city-scale and visa- versa. These conclusions addressed the first research objective of exploring a city-centric water system and the climate and socio-economic sensitivities and uncertainties of the system at a city-regional scale.

Stress testing the water systems model in WEAP with climate and socio-economic changes highlighted the system vulnerabilities for Lusaka. Vulnerabilities at a city-scale included quantifying the domestic demand met. At a city-regional scale the vulnerabilities quantified were the irrigation demand met, the average monthly hydropower generation and the hydropower reliability. The risk maps for city-scale and city-regional scale management scenarios combined these vulnerabilities to highlight the overall risk under climate change variation. The modelling, stress testing and developing risks maps addressed the second research objective of quantifying the vulnerabilities of African urban water security and its dependent sectors, due to external stressors, by developing a city-centric water resource model of the city of Lusaka reliant on the Kafue River Basin.

System vulnerabilities were based on the choice of the system stressors, consequences to the water system, the connections between the choices and consequences at a city-scale and a city-regional scale and the associated uncertainties of the stressor. Looking at water supply for domestic use and other water dependent sectors such as agriculture and hydropower, highlighted the trade-offs between the sectors of the water-energy-food nexus in ensuring water security at a city-centric level. The benefit of applying a bottom-up adaptation decision-support framework is that it highlights the challenges and chances for resilience.

Lusaka's water security faces challenges and chances for socio-economic, hazard and socio-ecological resilience. Socio-economic resilience will require financial support, information sharing and growth of institutional capacity; hazard resilience will require environmental management and consideration of climate change impacts; and socio-ecological resilience will require infrastructure development and social equity. The discussion developed from the case study results addressed the third research objective of informing short to medium-term decision-making by evaluating the water system's vulnerabilities, using an adaptation framework for decision-support.

6.2 Research contributions and limitations

This research contributes to the field of civil engineering, in the water field, and the social sciences, with a focus on decision making. The study has an academic and a practical contribution, based on the use of a case study. The research scope includes the use of climate information for decision-making, the trade-offs between water dependent sectors, the stressors and vulnerabilities for water security and the use of adaptive decision-support; all in an African context in which these applications tend to be underutilised (Calow et al., 2011; Jones et al., 2014).

The research was limited by minimal experience in energy and crop modelling which are key sectors in the case of Lusaka, Zambia. The study period was a limitation that didn't allow for detailed expansion of ideas and concepts with stakeholders, as a result the methodology does not include implementation recommendations for the conclusions drawn. The case study is unique to Lusaka, and therefore quantified results cannot be generally applied in an urban African context, but the common themes for challenges and chances for resilience can be more broadly applied. The urban water system is a complex one of which only a portion forms part of the scope of the research, this is not to say that elements outside the scope do not affect the elements within. Use of existing calibrated models that have already been peer reviewed minimised uncertainties and complexities associated with modelling and understanding urban water systems.

6.3 Recommendations for further research

Further research should be done in identifying and comparing the trade-offs and vulnerabilities between different urban centres. This would allow for the city-regional model to be expanded to a greater region that includes more urban centres and potentially other water-dependent sectors e.g. mining and solid waste managment. The system complexities were simplified for the scope of this research but factors such as water quality would greatly influence water security and resilience and should be considered in further research. More research is required into how the identified system vulnerabilities could be implemented into policies and how the existing frameworks support sector trade-offs. Further research specific to the study area of Lusaka would be developing detailed city-centric crop and hydropower models and identifying how their vulnerabilities translate economically.

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A. WATER RESOURCE GOVERNANCE

A.1 Existing Water Resources

Lusaka is situated on the southern part of the central plateau of Zambia. Lusaka has a humid subtropical climate, with a mean annual precipitation (MAP) of 882 mm (National Oceanic and Atmospheric Administration, 2012). The population projection for 2035 is 4.381 million from a population of 1.742 million in 2010 (Gauff Ingenieure, 2013).

In Zambia, the occurrences of extreme climatic events such as floods and droughts have been the result of climate variability and change and have disrupted socio-economic development (Department of Energy and Water Development 2007). Zambia has vast ground and surface water resources as well as renewable hydro energy sources for which changes in climate will affect the utilisation and exploitation of. In local communities in the Kafue river basin the following perceptions exist with regards to climate change; firstly, they have noticed changes in temperature with February to March becoming comparatively colder and September becoming cold and windy. Secondly, communities have observed rainfall changes involving a delay in the onset of rains from the end of October to the end November until mid-December, and the early end of the rainfall season in February instead of March (Department of Energy and Water Development 2007).

The Kafue River is a major tributary of the Zambezi River and has a catchment area approximately 20% the size of Zambia’s land area (Beekman 2016; Jones et al. 2014). The Kafue river basin is one of the most sensitive basins in Zambia and is subject to flooding (Department of Energy and Water Development 2007). Some built up areas of Lusaka have in the past been affected by floods in the Kafue basin as they are in low lying zones and are not properly drained. Lusaka is located on the south-eastern side of the Lower Kafue Basin near the Kafue Flats. The Kafue Flats is the second largest floodplain in Zambia and support some of the key economic activities of the country.

There are six main river systems in Zambia. For this study the Kafue River basin is the river system of interest as it the main surface water source for Lusaka. Table A-1 summarises basin characteristics for the Main Zambezi River basin and for the Kafue River Basin.

Table A-1: River Length and Basin Area of River Basins relevant for Lusaka (after JICA-MEWD, 1995)

River System	Length in Zambia (km)	Basin Area (km^2)		
		Total	In Zambia	Out of Zambia
Zambezi Main River Basin	1 700	687 049	268 235	418 814
Kafue River Basin	1 300	156 995	156 995	0

The Kafue river has its origins at the eastern end of the Zambezi-Congo watershed and flows to a point near Kitwe in a south-easterly direction (Nyambe and Feilberg, n.d.). From Kitwe the river flows south-westwards into the Itezhi-Tezhi Dam reservoir after which it turns eastwards and flows across the Kafue Flats into Kafue Gorge Dam reservoir. The southern parts of the basin have a lower tributary density when compared to the northern parts of the basin. Lusaka is situated approximately 130km north of Lake Kariba, one of the major lakes on the Zambian border with Zimbabwe (Nyambe and Feilberg, n.d.; The World Bank, 2010). The capital city is also situated approximately 100 km south of the Lukanga Swamp which is situated in the central province.

A.2 Water Resource Policies

This section elaborates on the national and local water resource policies and institutional frameworks for water. This includes existing acts and implemented innovations. These policies and frameworks are the basis of the water resource management that locally, Lusaka aims to achieve. They highlight the roles, responsibilities, visions and goals of the City. According to Jones et al. (2014) climate change mitigation and adaptation actions need to be embedded in national planning and be based on a firm understanding of climate information limitations. In National Development plans and sectoral strategies climate change has received little attention in the past (Jones et al., 2014). Allowing different institutions and stakeholders to be a part of the urban water management process ensures a more sustainable process (Closas, Schuring and Rodriguez, 2012, p.4).

To increase water security, flexible policy and legal frameworks will play a role in the ability to adapt to specific contexts and changing circumstances (UNU-INWEH, 2013, p.21). Some of the challenges associated with achieving water security include consideration for future scenarios in which policy is able to cope with the increasing complexity and uncertainty (UNU-INWEH, 2013, p.21). Institutional frameworks and their capacity to ensure water security goes beyond immediate management of water resources. Supporting water security requires a cross-sectoral enabling environment in which capacity for decision and policy making are developed at different levels (UNU-INWEH, 2013, p.24). institutions will need to be strengthened at different levels to incorporate climate change adaptation in the management of water resources (UN-Water, 2010, p.8). Adaptation is often underrepresented in national plans; to improve this policy should be guided by the strengthening of governance and water management systems, and building resilience through institutional strengthening (UN-Water, 2010, p.11). Water security can only be achieved with good water governance, which requires well-structured institutions that have the policy frameworks to support them. Inadequate institutional support can lead to unsustainable adaptation approaches (Rasul and Sharma, 2015b, p.2).

Constitution of Zambia and the National Water Policy (Government of Zambia, 2010b)

The Zambian Constitution Amendment Act No. 2 of 2016 includes that water should be under national control. By adopting an integrated water resource management (IWRM) system approach the National Water Policy promotes the establishment of comprehensive legal, institutional and regulatory frameworks for effective water resource management in Zambia. This management aims to be both equitable and sustainable. There exist a numerous provision for water resource management in the National Water Policy, these include (Beekman, 2016):

- Water resource assessments for both surface and groundwater sources,
- Improving access to surface and groundwater resources through their promotion and development and
- Complete strategic environmental assessments and environmental impact assessments on water resource development programs and projects.

The National Water Policy was first adopted in 1994 to ensure improvements in water resource management such that domestic water supply and sanitation were no longer the priority areas. This Policy was revisited in 2010 to provide a clear holistic vision for the water sector and to align the policy with international frameworks. The revisit also integrated cross-cutting issues such as climate change and re-examine the institutional frameworks and other existing legislation. The policy covers both water and water dependent sectors to ensure that activities are undertaken in a sustainable manner. It aims to align with the policies of other sectors. The policy measures and implementation focus on (i) water resources management, (ii) water resources development, (iii) water for food and agriculture, (iv) water for the environment, and (v) water for energy. Several cross-sectoral issues to the water sector are highlighted in the National Water Policy, namely: stakeholder and community level participation, water permit administration, data information, participation from the private sector, and climate change

Strategy for flood management for the Kafue River Basin in Zambia (Department of Energy and Water Development, 2007)

The Department of Energy and Water Development have developed a strategy for flood management for the Kafue River Basin in Zambia. Key thematic areas covered by the strategy relevant to the methodology of this study include (Department of Energy and Water Development, 2007):

- **Reducing vulnerability**: Vulnerability characteristically describes a communities' capacity to anticipate, cope with, resist and recover from impacts of natural and human induced hazards. The strategy aims to support and encourage flood resistant crops and cropping patterns that would potentially help income growth. Vulnerability reduction forms the foundation of the management actions that will be identified for the analysis. This includes encouragement and support of existing government and non-governmental programs that that aim to reduce vulnerability for the flood plain communities as well as improve their resource base.
- **Integrated approach to water resources development and flood management**: the defining characteristic for an integrated approach is integration expressed in a structural and a non-structural sense for both long-term and short-term measures allowing a participatory approach for decision making. This includes the development of national policies for integrated flood, land and water management. These policies should revise operation rules for dams and hydropower plants as well as priority rules for water supply systems. Consideration should be given to the integrated approach in priority allocation of the Kafue Basin WEAP model.
- **Protecting and conserving the environment**: The environmental impacts of flood and drought management options on the environment should be addressed. The modelling of land use regulations implemented to protect and develop watersheds will be used to address changing water resource effects on the environment.
- **Addressing weather and climate variability and change:** This is achieved through the preparation of long-term adaptation plans that are based on existing weather and climate forecasts and predictions. Development of the WEAP model for the study allows for weather and climate forecasts to be used for risk management
- **Coordination between various ministries and agencies:** The development of an inter-sector mechanism for coordination will support the planning and implementation of pre-disaster and post-disaster prevention and mitigation measures

Water Risk and Action Framework

The Water Risk and Action Framework (WRAF) was developed with the primary initiative of water security issues in Lusaka. The assessment of water risks and solutions (WRSA) is a critical component of the initiative from which basis measures to mitigate water risks can be identified (Beekman, 2016). The WRSA is relevant to this study as it broadly covers some of the same concepts as the FRACTAL project. According to Beekman (2016) the WRSA comprises:

- An analysis of the current and future potential water security threats including their root causes in the existing legal and institutional frameworks, infrastructure and water resources.

Investigating the situation of awareness regarding the groundwater quality and groundwater quantity, Kafue River flows and water supply and access to sanitation services.

- An analysis of potential changes in Lusaka's water security within 5-10 years using model-based scenarios
- An assessment of the socio-economic of the situation for potential future and current water security
- An address of the multi-criteria solutions for water risk

Water Resource Management and the Water Supply and Sanitation Act (Beekman, 2016)

The Zambian government has a law referred to as the Water Resource Management Act that facilitates to entrench IWRM by means of establishing river management organizations. The Kafue basin was chosen as the pilot catchment for the initiative prior to it being duplicated in subsequent catchments.

The Water Supply and sanitation act provides an outline for the procedures to be followed and measures to be taken in the case of a water supply shortfall. It also outlines the rights of water supply services and prohibits activities that may pose a threat to water and sanitation facilities that are utility owned.

Vision 2030 (Republic of Zambia, 2006)

Vision 2030 is a long-term plan outlining national and sector goals for desirable socio-economic indicators. In the context of this research, the key 2030 focus areas are:

- Alleviating poverty, hunger and deprivation: having implemented institutional measures to provide socio-economic activities to the underprivileged
- Healthy communities with low mortality and disease rates
- Well planned and secure cities and provincial areas that provide basic amenities: promoting development and public-private partnerships
- Mutually co-existing societies and natural habitat with a rich bio-diversity: having improved the laws and institutions that will support the sustainable use of environmental resources bearing in mind the wellbeing of the population

The vision acknowledges the lack of water supply infrastructure services as a key delay to the housing development. stating that the country has not established how to prevent pollution of, or fully harness its available surface and ground water sources. National development Plans (NDPs) are used to operationalise Vision 2030. The Vision aims to achieve sustainable water resource management that is also integrated; this includes the upgrading of unplanned settlements to have access to clean water.

7th National Development Plan (Government of Zambia, 2017)

The 7th national development plan covers the period 2017-2021 and is multi-sectoral approach focussed on "Accelerating development efforts towards Vision 2030 without leaving anyone behind" by creating an economy that is diverse and resilient. The plan highlights that planning processes should be both top-down and bottom-up; ideally starting at a community level and being passed on to a district, provincial and ultimately national level. For the Lusaka province, the focus areas include the need to invest in energy, for economic improvement, and support the agriculture sector. National water reforms were taken by the government to create utility companies in both urban and peri-urban areas, which improved the quality of the service, but infrastructure was still identified as a constraint as it led to approximately half of the reticulated water being wasted.

There is potential to increase the agricultural outputs from Zambia since the fertile land and vast water resources are not yet fully tapped. This will allow for the economy will not become over reliant on its high exports of copper and cobalt. The urbanisation in Zambia, especially in Lusaka is a development challenge as it has led to unplanned settlements in which people have limited access to adequate infrastructure. The 7th NDP highlights that policies should address the socio-economic challenges and opportunities associated with rapid urbanisation. The NDP outlines the current climate change impacts in Zambia and that the droughts, rising temperatures and variations in rainfall patterns will negatively impact the economy. Evidence of this is offered through the energy sector, where poor rainfall patterns have affected hydropower generation. The plan includes climate change adaptation measures that aim to reduce the environmental risks of water insecurity. The following key strategic areas are the focus of the 7th NDP that should be highlighted in the context of this research:

- An improved policy environment with evidence of transparency and accountability
- Improving service delivery
- Governance that is inclusive and democratic

The plan has development outcomes that pertain to the water-energy-food nexus. In the agriculture sector the country plans to promote the use of climate smart techniques like conservation farming. In the energy sector the country has yet to diversify its means of generating electricity, which has historically lead to rationing during times of drought. The plan envisions a growth of 15% for power sources other than hydropower. They plan outlines the importance of improving access to water supply and sanitation for enhancing human development; the strategy being to improve the provision and availability of adequate and safe water as well as enhancing research in the sector.

Water Strategy for climate adaptation in SADC (GWP-Southern Africa, 2011)

The goal of the climate change adaptation strategy is to improve the resilience of the water resources in SDAC to climate impacts, at a regional, river basin and local scale through adapted integrated water resource management. Adaptation has been identified as a priority in Southern Africa in the context of climate vulnerabilities, because Africa's contribution to the global emissions is small. Climate change impacts already affect majority of Southern African countries; future development and climate change adaptation will be linked. The SADC water strategy for climate adaptation emphasises the adoption of water resource management practice, to minimise the vulnerabilities to the water sector and as a tool for climate resilience in the SADC region.

National Climate change response strategy (Government of Zambia, 2010a)

The National Climate Change Response Strategy (NCCRS) was developed to facilitate and support responses to climate change in the Republic of Zambia. The NCCRS was set up to contribute to the objectives of the United National Framework Convention on Climate Change and aims to promote interventions that take advantage of the opportunities that climate change presents; these opportunities include advances in technology. The NCCRS describes that although Zambia has an abundance of water resources it does not make it exempt to the impacts of climate change. It highlights that changes in rainfall will affect the country's socio-economic development. This has been evident in the impacts of La Niña and ENSO rainfall events, which have resulted in either floods or droughts respectively. Both flood and drought conditions have socio-economic effects such as the spread of disease, decrease in agricultural production and destruction of infrastructure- especially in the case of flooding and hydropower dams. It explains that the rising temperature trend will increase evaporation which will decrease the volume of water bodies, namely hydropower dams. This hydro-vulnerability will also lead to power cuts which will have effects beyond the industrial sector and may lead to higher deforestation rates.

A.3 Water Resource Institutional Frameworks

There are institutional dynamics that play a role in the Water security of Lusaka. To encourage collaboration between the relevant institutions LuWSI was established as a collaboration system to define a common water agenda. The roles and mandates of some of the key institutional frameworks for managing water security are summarised in figure A-1.

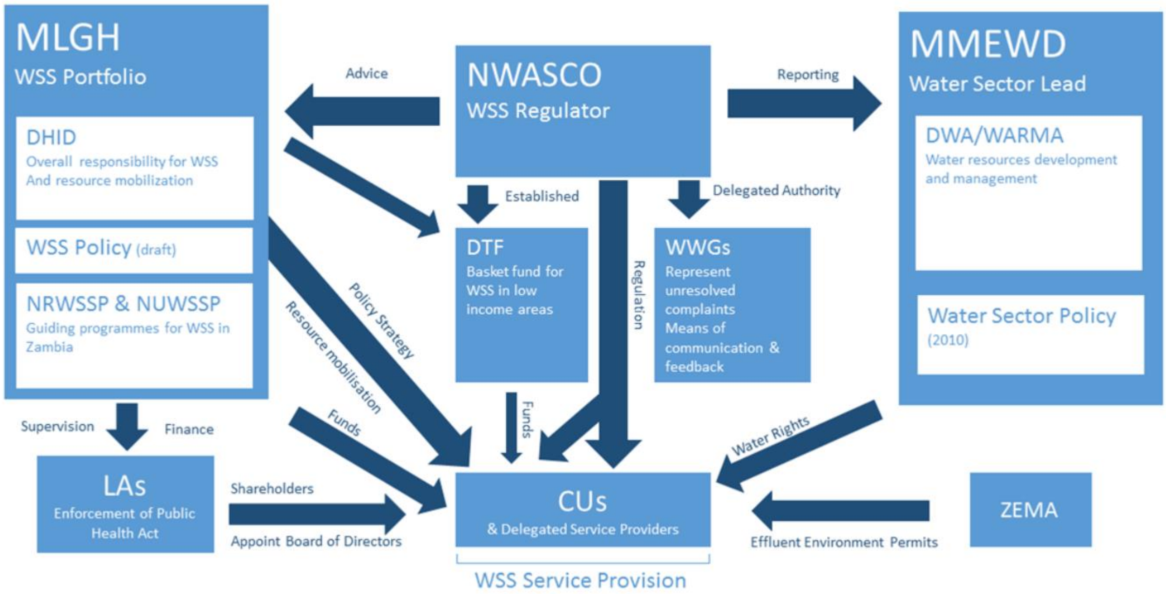


Figure A-1:Existing institutional frameworks for managing the water and Sanitation Sector (Beekman, 2016, p.31)

Lusaka City Council (LCC) (Lusaka City Council, 2018)

The Lusaka City Council's mandate is aligned with the Local Government Act No. 281. The LCC has a political wing, which is headed by the mayor, and an administration wing, led by a town clerk. The LCC operates as a local authority that represents local Government using local leaders, namely councillors. The following are the functions of the LCC which fall into the scope of this research

- provision and maintenance of clean water supplies and establishing water mains
- conservation of natural resources
- storing and preserving agricultural goods
- administering systems for community participation in development

Using a representative system on their council the LCC ensures that local communities participate in the decision-making process, this is to enhance self-governance through participation.

National Water and Sanitation Council (NWASCO) (NWASCO, 2014)

NWASCO's role is to regulate the water supply and sanitation services to ensure the services are safe, affordable and sustainable. Their core functions are to provide efficient and sustainable WSS through licence provision, advisory to government, and providers on procedures for handling consumers, enforcing sector standards and guidelines; and publicising information to consumers. NWASCO works closely with the Ministry of Local Government and Housing (MLGH); who has the mandate to coordinate water supply and sanitation in an urban context, using local authorities (LAs). It also works with the Ministry of Water Development, Sanitation and Environmental protection (MEWD).

Water Resources Management Authority (WARMA) (WARMA, 2016)

WARMA was established in 2012 and their core function is to “promote and adopt a dynamic, gender-sensitive, integrated, interactive, participatory and multisectoral approach to water resources management and development that includes human, land, environmental and socio-economic considerations, especially poverty reduction and the elimination of water borne diseases, including malaria” (WARMA, 2016). the other functions of WARMA are to implement the water resource management act, allocate water permits and licenses, and promote sustainable use and protection of the available water resources.

Lusaka Water & Sewerage Company (LWSC) (LWSC, 2013, 2017)

LWSC provides water and sanitation services in the Lusaka province as a commercial water utility. Their mission is the provision of quality water and sanitation services at sustainable levels, both commercially and environmentally. The company was created as part of a reform process, starting operations in 1990, and was originally part of the Lusaka City Council. Some of their objectives as a corporate are to improve profitability, reduction of non-revenue water and provision of reliable water and sanitation. LWSC works with licensed water trusts to provide water to the densely populated peri-urban areas. Their main challenges are dealing with demands that are higher than their supply capacity, water loss, aged infrastructure and increasing operating costs.

ZESCO (previously Zambia Electricity Supply Corporation Limited)

ZESCO is the Zambian public electricity utility that generates, transmits and distributes electricity to Zambia. ZESCO was formed in 1970 and has the Government of Zambia as its sole shareholder. They aim to provide safe and reliable electricity. ZESCO is Zambia’s largest power company, generating approximately 80% of the consumed electricity in Zambia. Their generation in 99% hydro-power of which a 23.2% share is used in the Lusaka province.

Zambia Environmental Management Authority (ZEMA) (ZEMA, 2018)

ZEMA was established through the Environmental Management Act No. 12 of 2011 as an independent environmental regulator. Its mandate is to protect the environment, control pollution as a coordinating agency. ZEMA’s functions include, but are not limited to:

- Monitoring natural resource usage trends and the impacts the usage has on the environment; and
- Promoting and initiating environmental management research and ensuring that environmental concerns are included in national planning.

B. ALTERNATIVE BOTTOM-UP APPROACH

B.1 Robust Decision Making (RDM)

Robust Decision Making (RDM) is a framework for supporting management and decision processes under climate change and other uncertainties by identifying key vulnerabilities and risk management (Groves et al., 2014). The main focus being to identify resilient options or those that achieve the desired result when considering multiple future scenarios (CDM, 2011). Groves et al. (2014) and Lempert et al. (2011), in their research, identify and describe the key elements of RDM.

The first key element begins with a candidate decision by reversing the order of the predict-then-act analysis. Through the support of an iterative and participatory dialogue with stakeholders and decision makers to support the developed analytic results and gain new insights into future analysis RDM identifies the conditions under which certain decisions are vulnerable. By identifying a wide-range of uncertainties, as climate change is only one of the uncertain factors affecting water management, could result in other plausible futures to be explored. The uncertainty is characterized in terms of its measurable effect on the ability of the decision to achieve set performance metrics.

Secondly the RDM method characterizes uncertainty with multiple future views. Through the exploration of a spectrum of possible future climates, using climate projections based on different methods, RDM investigates the differences between scenarios as well as alternative futures. By generating numerous simulation model runs the method uses statistical analysis to summarise the most-important scenarios for decision makers.

The third key element is that of seeking robust strategies, not necessarily optimal ones, which are robust across a few performance metrics. Robust strategies are those that would achieve set utility goals across a broad range of futures instead of those ideal under a single set of assumptions. As robust decisions perform well independent of a wide range of futures they are sensitive to a small set of potential uncertainties.

The water management planning tools based on RDM are designed to be adaptive in response to new information, this allows for acceptable outcomes regardless of projected future conditions not holding true. Identifying key vulnerabilities to help highlight the vulnerability of water resources to climate change and other uncertainties. This information provides a guide to developing adaptation strategies. The RDM process has a series of steps that adapted based on the application. In the first step analysts, decision makers and stakeholders have a participatory scoping dialogue during which uncertain factors that may play an important role in future performance are defined. A tool for defining these factors is a XLRM Matrix, which documents the uncertain exogenous factors (X), the management decisions and policy levers (L), the performance metrics and measures (M), and the relationships or models relating the uncertainties (R) (Groves et al., 2015). Developing an XLRM matrix is both a qualitative and a quantitative process. The process involves showing ranges of plausible values for the uncertain factors (X); and defining thresholds for performance metrics (M) to identify the futures in which management strategies will meet utility goals; an example matrix is represented in **Table B-1**

Table B-1: Example of a RDM XLRM matrix (Groves et al., 2015).

Uncertainties (X)	Decisions, options or levers (L)
▪ Climate informed conditions ▪ Demand for existing citizens ▪ Hydrology conditions ▪ Population growth	▪ Current infrastructure ▪ Other adaptation options to be determined
Relationships or models (R)	**Performance metrics (M)**
▪ WEAP as a hydrology model ▪ Yield model	▪ Reliability index ▪ Safe yield

The second step focuses on evaluating the system under uncertainty. This involves using the uncertainties, from step one, to develop futures to be evaluated in the model. This model also estimates the future performance of each strategy. The system performance is estimated based on the metrics (M) defined in step one. The third step includes a vulnerability assessment where "vulnerable conditions" are defined. This combines external uncertainties that would lead to utility goals not being met. The basic approach is to define easily interpretable conditions that lead to vulnerabilities.an example for the XLRM matrix above would be demand greater than 95 million gallons per day and climate projections 6-10 degrees warmer/drier. The final step in the RDM process is the development of adaptation options to address the vulnerabilities. Step four identifies the uncertain future conditions in which the utility goals are not met. Based on the outcomes of the vulnerability assessment, either further dialogue would be necessary (step one) or alternative strategies would need to be established (step two and three) (Groves et al., 2014). Through iterations RDM explores a broad range of possible strategies without uncertain future parameters.

C. CITY LEARNING LAB ENGAGEMENT

Year	Dates	Type of engagement
2015	Project-wide engagement: 12-14 August FRACTAL inception workshop report	
2016	1-2 March	First meeting in Lusaka
	4-6 April	Trip to Lusaka
	6-7 September	Inception workshop and Learning Lab 1
2017	25-27 January	Day 1: City dialogue 1 Day 2: Training workshop
	4-7 July	Day 1: Training workshop Day 2: Learning Lab 2 Day 3: High-level breakfast and field trip
	4-5 October	Media training workshop: water security
	27-29 November	Field trip and Learning Lab 3
2018	13-14 November	Learning Lab 5 (Final)
	16 November	High Level Breakfast

Learning lab 1 (7 September 2016: Chaminuka Lodge) attendance register

Participant Name	Organisation
Piotr Wolski	University of Cape Town
Duncan M. Musama	Disaster management and mitigation unit
Bwalya E. Funga	Lusaka City council
Jonathan Mwanza	GIZ/Lusaka City Council
Beverly M. Mushili	University of Zambia
Tasila Banda	Climate Change Secretariat
Orleans Mfune	University of Zambia
Richard Jones	MET OFFICE –Hadley UK
Michael M. Museba	Ministry of Local Government and Housing
Curtis Muleya	National Water SCO
Romas Kamanga	ZESCO
Douty Chibamba	University of Zambia
Teddy Mwenya	Water Resources Management Agency
Gilbert Siame	University of Zambia
Mulimba Yasini	Lusaka City Council
Maliwa Muchuh	Lusaka City Council
David Nonde Mwamba	GIZ
Francis E. Ngomba	Lusaka City Council
Suman Jain	University of Zambia
Di Scott	University of Cape Town
Christopher Kaniki	Zambia Electricity Supply Company
Enock Sakala	University of Zambia
Brenda Tembo	Zambia Housing and Poor Peoples Federation
Farai Shumba	Peoples Process on Housing and Poverty in Zambia
Alice McClure	Climate Systems Analysis Group /University of Cape Town
Kambili Chilufya	Zambia Environmental Management Agency
Trophius Kufanga	Lusaka City Council
Josephine Chiila	Lusaka City Council
Brenda Mwalukanga	University of Zambia / Lusaka City Council
Mukonde M. Malwa	University of Zambia
Wilma Nchito	University of Zambia
Chilala Haankuku Kapulu	University of Zambia
Muchimba Muvumbo	University of Zambia
Christopher Jack	Climate systems analysis group/University of Cape Town

Learning lab 2 (6 July 2017: Radisson Blu, Lusaka) attendance register

Name	Organisation
Davison Muchadenyika	Climate systems Analysis Group/University of Cape Town
Gilbert Siame	University of Zambia
Nkulumo Zinyengere	South North
Namutoka David	University of Zambia
Chipampata Musonda	University of Zambia
Bwalya Funga	Lusaka City Council C
Wyness Zimba	GIZ
Richard Jones Met Office	Met Office
Chris Jack	University of Cape Town
Rebecca Ilunga	Aurecon
Orleans Mfune	University of Zambia
Esther Mwambazi	Lusaka City Council
Kalumba Kombe	Lusaka City Council
Audrey Daka	Lusaka City Council
Farai Shumba	Zambia homeless and poor people’s process
Enock Sakala	University of Zambia
Mukusekwa Kapembwa	Lusaka City Council
Mununga Mungalu	Lusaka water and sewerage company
Estella Nakaluzwe Mbulo	Lusaka City Council
Trophius Kufanga	Lusaka City Council
Mutukwa Musole	Lusaka City Council
Brenda Tembo	Zambia Homeless and Poor Peoples Federation
Veronica Katulushi	Zambia Homeless and Poor Peoples Federation
Sinachikupo Kenneth	Zambia Meteorological Department
Mpelele Elijah	University of Zambia
Chisoko Jones	Lusaka City Council
Suman Jain	University of Zambia
Kasenga Hara	National water and sanitation council
Brenda Mwalukanga	FRACTAL

Learning lab 3 (27-29 November 2017, Chita Lodge, Kafue) attendance register

Name	Organisation
Isaac Henry Banda	Lusaka City Council
Mununga Mungalu	Lusaka Water and Sewerage Company
Edgar C.Mulwanda	Lusaka City Council
Mando Chitondo	Giz/LuWSI
Bettina Koelle	Red Cross Climate Centre
Audrey Daka	Lusaka City Council
Belinda Lubasi	Lusaka City Council
Namwezi Nanyangwe	WARMA
Liz Daniels	Stockholm Environmental Institute
Peter Chisanga	MNDP-UNJP
Misheck Banda	MLG
Dianne Scott	University of Cape Town
Innocent Mwansa	Lusaka City Council
Chrispin Lukwanda	NWASCO
Wilma Nchito	University of Zambia
Gilbert Siame	University of Zambia
Richard Jones	MOHC
Rebecca Ilunga	Aurecon
Sukaina Bharwani	Stockholm Environmental Institute
Chris Jack	University of Cape Town
Belinda Lubasi	Lusaka City Council
Misheck Banda	MLG
Mwanza Jonathan	SHTC
Innocent Mwansa	Lusaka City Council
Albert Siame	University of Zambia
Boyd Kaoma	Lusaka City Council
Dorothy Jato	WARMA
Veronica Katulushi	ZHPPF
Belinda Lubasi	Lusaka City Council
Isaac H Banda	Lusaka City Council

D. WEAP MODEL INPUTS

Population

Scenario year	Population	Reference
1960	769 400	(Central Statistical Office Zambia, 2018)
1990	1 000 000	
2017	2 426 900	
2020	$2\ 426\ 900 \times (1+0.049)^3$	
2035	$(2\ 426\ 900 \times (1+0.049)3) \times (1+0.03)^{15}$	

Effective precipitation

If(KGU sub precip[mm]<=250, KGU sub precip[mm]*(125 -(0.2*KGU sub precip[mm]))/125, 125 +(0.1 *KGU sub precip[mm])) (The World Bank, 2010, p.115)

Evapotranspiration

Month	Temperature (℃) to Evapotranspiration (mm) conversion
January	$3.2473^* T_{average} +53.61$,
February	$2.8419 * T_{average} +46.838$
March	$3.3789^* T_{average} +56.871$
April	$3.36^* T_{average} +61.488$
May	$3.286^* T_{average} +68.875$
June	$2.925^* T_{average} +68.475$
July	$3.2085^* T_{average} +76.202$
August	$4.03^* T_{average} +84.429$
September	$4.92^* T_{average} +83.788$
October	$5.27^* T_{average} +78.154$
November	$3.885^* T_{average} +57.344$
December	$3.3868^* T_{average} +54.797$

Demand sites

	Urban population	Peri-urban population	Reference
Annual activity level	1960: population x 0.3 1990: population x 0.325 2017: population x 0.325 2020: population x 0.5 2035: population x 0.75	1960: population x 0.7 1990: population x 0.675 2017: population x 0. 675 2020: population x 0.5 2035: population x 0.25	(Gauff Ingenieure, 2013, p.2-13)
Annual water use rate	270l/c x 365.25	90l/c x 365.25	(Gauff Ingenieure, 2013, p.2-14)
Loss rate	1960: 65%; 1990: 65%; 2017: 45%; 2020: 30%; 2035: 15%		

Catchments

	Area	Kc	Reference
Sugar cane	I1: 35 021 ha I2: 39 971 ha I3: 65 971 ha	0.95	(The World Bank, 2010, pp.84-85)
Kafue Flats sub basin	46 167 km^2		(Pöyry Energy GmbH and Kling, 2011; Spalding-Fetcher et al., 2014)
Kafue Gorge sub-basin	4 348.9 km^2		

Reservoirs

	Kafue flats	Kafue Gorge Upper	Reference
Storage capacity	9 498 Mm^3	948.8 Mm^3	(Pöyry Energy GmbH and Kling, 2011; Spalding-Fetcher et al., 2014)
Maximum hydraulic outflow	0.5*(PrevTSValue(Storage Capacity)) *0.1389 +0.5* (PrevTSValue (Storage Capacity,2)*0.1389)	ZDSS Maximum discharge	
Losses	ZDSS losses and (ΔETO-Eactual)		

Reservoir operation

	Kafue Gorge Upper	Reference
Top of conservation	945 Mm^3	(Pöyry Energy GmbH and Kling, 2011; Spalding-Fetcher et al., 2014)
Top of buffer	Top of inactive	
Top of inactive	880	
Buffer coefficient	0.1	

Hydropower parameters

	Kafue Gorge Upper	Kafue Gorge Lower	Reference
Max turbine flow (m^3/s)	252	347	(Pöyry Energy GmbH and Kling, 2011; Spalding-Fetcher et al., 2014)
Tailwater elevation	582 m		
Plant factor	93%		
Generating efficiency	88%	90%	
Fixed head (m)		195	
Energy demand (GWH)	5 160/12	2 400/12	

Volume-elevation curve

Kafue Gorge Upper	**Ref:** (Pöyry Energy GmbH and Kling, 2011; Spalding-Fetcher et al., 2014)	**Kafue Flats**	**Ref:** (Pöyry Energy GmbH and Kling, 2011; Spalding-Fetcher et al., 2014)
Volume (Mm^3)	**Elevation (m)**	**Volume (Mm^3)**	**Elevation (m)**
0	911	0	0
785	964	15	976
928	975	77	977
941	976	303	978
954	977	989	979
1188	995	2 143	980
		3 616	981
		5 285	982
		7 094	983
		8 039	983.5
		9 006	984
		9 498	984.25

Groundwater

	Municipal	**Private**	**KF loss**
Initial storage	300*0.8*0.08*100 Mm^3 (JICA, 2008, p.4-8)	300*0.8*0.08*100 Mm^3 (JICA, 2008, p.4-8)	
Maximum withdrawal	5.6 Mm^3	5.27 Mm^3	No withdrawal
Natural recharge	Key\KGU sub precip[mm] *MonthlyValues(Jan, 0.063, Feb,0.063, Mar, -0.063, Apr,-0.063, May, -0.063, Jun, -0.063, Jul, -0.063, Aug, -0.063, Sep, -0.063, Oct, -0.063, Nov, -0.063, Dec, 0.063)*(3000/1000) (JICA, 1995, p. D-72)		

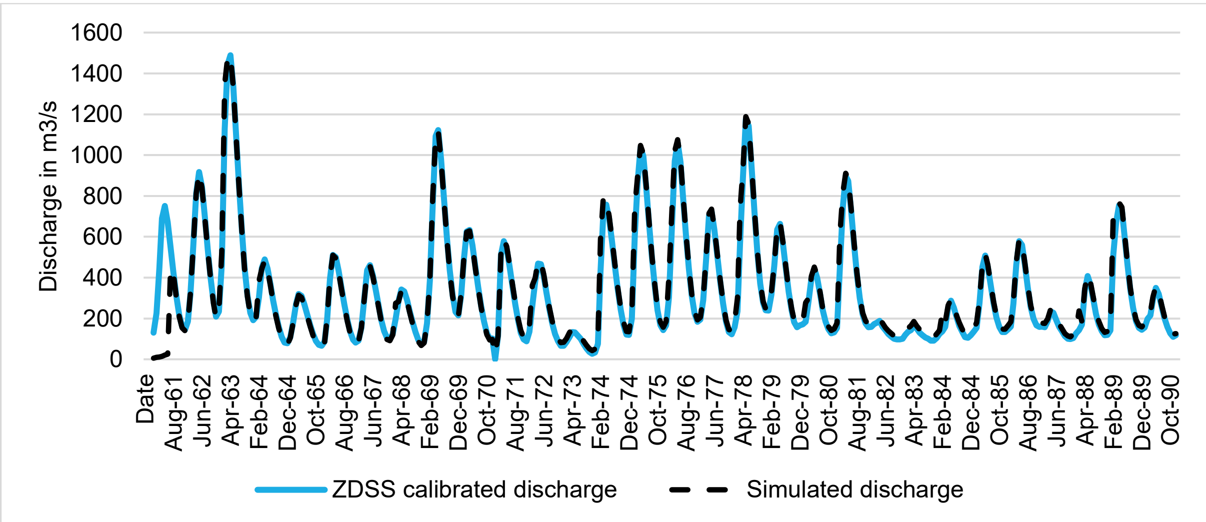
Local reservoirs

	Iolanda	**Kiosks**	**Reference**
Storage capacity (Mm^3)	1960: 0.09 * 365.25 1990: 0.09 * 365.25 2017: 0.095 * 365.25 2020: 0.48 * 365.25 2035: 0.64 * 365.25	0.005534*0.6	(JICA, 2009; Gauff Ingenieure, 2011, 2013)
Maximum hydraulic outflow (m^3/s)	7.5	(0.005534*0.6)/(24*3600)	

Transmission links (m3/day) (JICA, 2009; Gauff Ingenieure, 2011, 2013)

To From	Urban	Peri-urban	Kiosks	Iolanda	Sugar cane
Private GW	170 000				
Municipal GW	1960-2017: 130 000 2020-2035: 180 000	5534*0.4	5534*0.6		
Kiosks		5534*0.6			
Iolanda	1960: 90 000 1990: 90 000 2017: 95 000 2020: 480 000 2035: 640 000				
Kafue				1960: 90 000 1990: 90 000 2017: 95 000 2020: 480 000 2035: 640 000	1 246 000

Baseline simulated versus observed streamflow downstream of Kafue Gorge Upper (Pöyry Energy GmbH and Kling, 2011)



E. CLIMATE RISK NARRATIVES

These climate risk narratives were developed by Dr C Jack (UCT, CSAG) and Dr R Jones (Met Office-Hadley Centre) (2017)

Narrative 1: Drier, hotter

Emerging from a severe drought in 2015/2016 that constrained both water and power supplies and disrupted food prices and availability in the region Lusaka enjoyed a number of relatively normal rainfall seasons though average temperatures continued to slowly rise. However, in the 2020s another even more severe drought that persisted for 3 seasons and was combined with temperatures 1.5ºC higher than usual, caused severe disruption in the region. Higher urban populations and increased service delivery had already pushed water demand levels higher than previously seen.

Higher temperatures contributed to increased evaporation and reduced runoff when the weak rains did fall. This resulted in extremely low river levels in the Kafue and upper Zambezi which shutdown hydro power generation in both the Kafue gorge and Kariba power stations causing widespread power cuts. While groundwater was still viable in the greater Lusaka area, water tables dropped significantly limiting yield. Reduced subsurface flow reduced water quality.

Regional agriculture in the Kafue flats was also impacted by both higher temperatures and reduced rainfall, raising local food prices and forcing the import of significant amounts of food for the city. The drought ended after three dry seasons, but the end was marked by very intense rainfall that caused widespread flooding both within Lusaka itself and in surrounding regions, damaging roads and, critically, damaging some of the Kafue pumping stations.

Following the big drought, rainfall recovered for several years, but increasing population in the city continued to increase water demand in the city prompting extension of local well fields and another upgrade to the Kafue pipeline infrastructure.

In the 2040s Lusaka and the region continues to experience cycles of wetter and drier seasons but average temperatures around 1.5°C higher than the end of the 20th century and dry seasons are far more common with multi-year droughts occurring at least once a decade.

Narrative 2: No rainfall change, warmer

Emerging from a severe drought in 2015/2016 that constrained both water and power supplies and disrupted food prices and availability in the region Lusaka enjoyed several relatively normal rainfall seasons though average temperatures continued to slowly rise.

Higher temperatures contributed to higher evaporation and reduced runoff. This resulted in on average lower river levels in the Kafue and upper Zambezi and in dry years the result was limited hydro power generation in both the Kafue gorge and Kariba power stations causing widespread power cuts. While groundwater remained viable in the greater Lusaka area, water tables dropped significantly limiting yield. Reduced sub-surface flow reduced water quality.

Regional agriculture in the Kafue flats was also impacted by higher temperatures and increased irrigation demand, raising local food prices. Increasing population in the city continued to increase water demand prompting extension of local well fields and another upgrade to the Kafue pipeline infrastructure. In the 2040s Lusaka and the region continues to experience cycles of wetter and drier seasons but average temperatures around 2ºC higher than the end of the 20th century.

Narrative 3: Mixed rainfall change, warmer

Emerging from a severe drought in 2015/2016 that constrained both water and power supplies and disrupted food prices and availability in the region Lusaka enjoyed several relatively normal rainfall seasons though average temperatures continued to slowly rise. However, in the 2020s another even more severe drought that persisted for 3 seasons and was combined with temperatures 1.5°C higher than usual, caused severe disruption in the region.

Higher temperatures contributed to higher evaporation and reduced runoff when the weak rains did fall. This resulted in extremely low river levels in the Kafue and upper Zambezi which shutdown hydro power generation in both the Kafue gorge and Kariba power stations causing widespread power cuts. While groundwater was still viable in the greater Lusaka area, water tables dropped significantly limiting yield. Reduced sub-surface flow reduced water quality.

Regional agriculture in the Kafue flats was also impacted by both higher temperatures and reduced rainfall, raising local food prices and forcing the import of significant amounts of food for the city. The drought ended after three dry seasons, but the end was marked by very intense rainfall that caused widespread flooding both within Lusaka itself and in surrounding regions, damaging roads and, critically, damaging some of the Kafue pumping stations.

Following the big drought, rainfall recovered for several years, but increasing population in the city continued to increase water demand in the city prompting extension of local well fields and another upgrade to the Kafue pipeline infrastructure.

In the 2040s Lusaka and the region continues to experience cycles of wetter and drier seasons but average temperatures around 2°C higher than the end of the 20th century and dry seasons are far more common with multi-year droughts occurring at least once a decade.

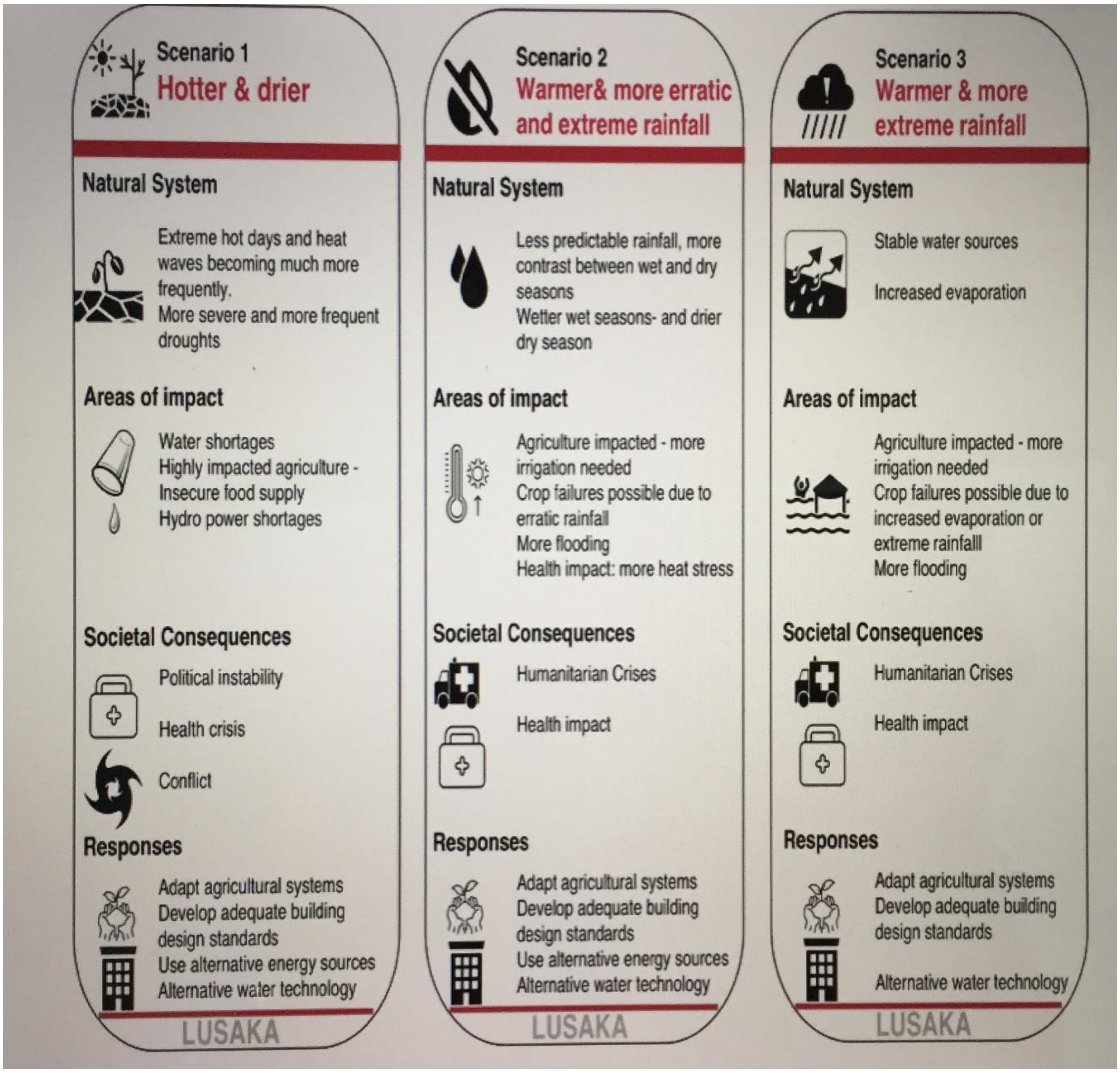


Figure E-1: Illustrated climate risk narratives