Bottom-Up Adaptive Decision-Support for Resilient Urban Water Security: Lusaka Case Study

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FRACTAL

FUTURE RESILIENCE FOR AFRICAN CITIES AND LANDS

FRACTAL

The Future Resilience for African Cities and Lands (FRACTAL) project aims to address the challenge of providing accessible, timely, applicable and defensible climate information that is needed by decision makers operating at the city-region scale in southern Africa. FRACTAL has been running since June 2015. It is part of the Future Climate for Africa (FCFA) multi-consortia programme. FCFA's major objective is to generate fundamentally new climate science focused on Africa, and to ensure that this science has an impact on human development across the continent. FCFA is funded by the Department for International Development (DFID) and the Natural Environment Research Council (NERC).

These knowledge products have been developed to share findings from the research in the hope of fostering dialogue and eliciting feedback to strengthen the research. The opinions expressed are therefore those of the author(s) and are not necessarily shared by DFID, NERC or other programme partners.

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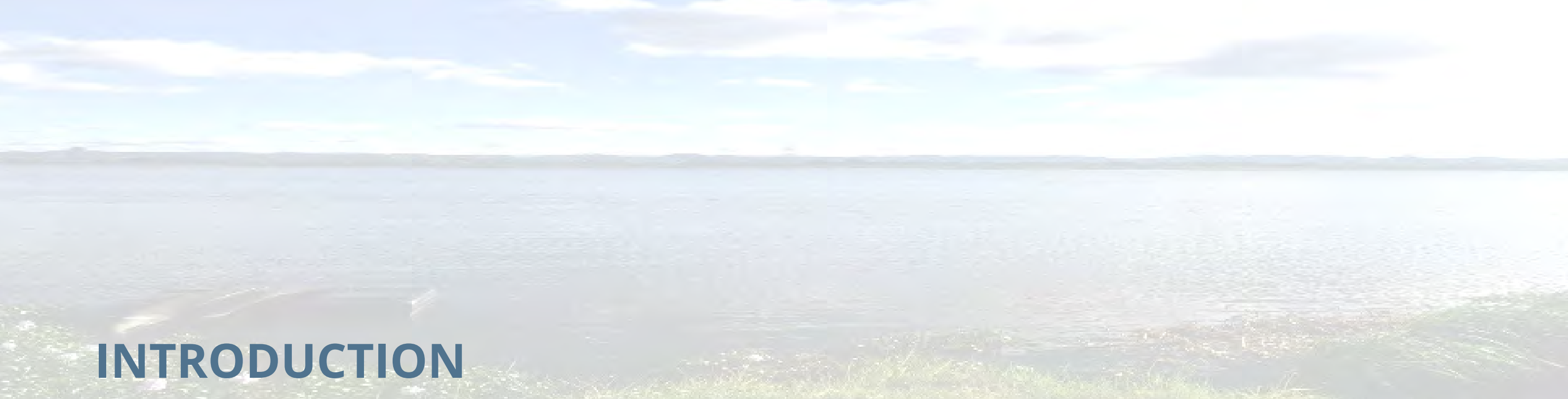


INTRODUCTION

Background

The Future Resilient African Cities and Lands (FRACTAL) research program is led by the Climate Systems Analysis Group (CSAG) at the University of Cape Town and includes researchers from a wide range of partner organisations including universities, African cities, and the private sector. FRACTAL aims to advance scientific knowledge about regional climate and to enhance the integration of this knowledge into urban decision-making, thus enabling climate-resilient development pathways in cities in Africa. Focusing on urban areas in southern Africa, the project works with academics and decision makers across nine cities in the region through a collaborative co-production process.

Water, and its security, is central to sustainability and development. To properly address the challenge of water security, water managers and policy makers need to identify the vulnerabilities of water systems and the consequences thereof. Sustainably managed, formalised water systems have lower levels of risk to their water security when they are resilient and less vulnerable to external stressors. The sustainable management of water security is challenged by the uncertainty of future climate change and other contributing factors.

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, and the capacity to be adaptable when stressed or changed (Tyler & 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 these 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 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, 2015; Cullis et al., 2018). A gap exists in the research around 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). 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).

African cities are in the process of significant social, economic and demographic transformation, which is 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).

Aims and Objectives

The aim of the research is to improve urban water decision-making under uncertainty at a city scale, through a case study of the city of Lusaka in Zambia. Lusaka is a co-dependent city of the Kafue River Basin. The study took a city-centric approach to adaptive decision-support, to better inform African city water systems' resilience to climate and socio-economic changes. The goals of the research are therefore to:

1. Explore an African city-centric water system and the climate sensitivities of the system.
2. Quantify the vulnerabilities of African urban water security and its dependent sectors, due to external stressors.
3. Inform short to medium term decision-making using Decision-Scaling (DS) as an adaptation framework for decision support, by evaluating system vulnerabilities.

Water Security in Africa

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 and variability on water, and its dependent energy and food supply systems, is required (UNESCO, 2012; Cullis et al., 2015). Ensuring that policy and decision makers can respond to the long-term impacts of climate and socio-economic changes is important in promoting development that is resilient.

The practical application of the research approach is to create a holistic understanding of urban water decision-making, management and security, in an African context, and to investigate where challenges arise and opportunities exist for adaptation frameworks in decision-making. Identifying these challenges and opportunities gives a platform for developing resilient city-regional water systems.

Changing demographics, increased urbanization, changes in demand and to the hydrological cycle will all impact on the availability of water, while sectoral competition between water dependent sectors will also put a strain on the resource (UNU-INWEH, 2013). Decisions made that affect the water sector are often made in broader policy frameworks and not exclusively by water managers, making trade-offs and multi-sectoral coordination important considerations for decision-making.

Water Dependent Sectors

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). 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 or sectors may be at the expense of the security for others. This highlights the importance of finding trade-offs for water security.

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). Some of the potential vulnerabilities to water dependent sectors include: flood shortages; 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 issues already experienced in many urban areas. Ways need to be found for the systems to have a greater adaptive capacity (UNESCO, 2012; Ray and Brown, 2015). In contrast to climatic changes, socio-economic changes, such as population growth predictions and government investment in infrastructure, have an associated certainty. This makes them valuable indicators for sectoral vulnerabilities, as potential water system impacts can be better estimated (Calow et al., 2011).

Central to the sustainable development of water-dependent sectors is the water-energy-food nexus (UNU-INWEH, 2013; UN-Water, 2018a). The intrinsic linkages between these sectors requires a sustainable approach to their security, resilience and management. Globally, the largest consumer of the world's freshwater is agriculture and 90% of power generation is water intensive (AMCOW, CDKN and GWP, 2012b; UN-Water, 2018a). These three sectors also underpin several of the sustainable development goals (SDGs). However energy and food's dependence on water, has meant that decision makers in all three sectors are focusing on integrated water resource management (IWRM) as part of their policy to ensure secure water supply (UN-Water, 2018a). Water in Africa as an energy source (i.e. hydropower) has the potential to support economic growth and aid in climate change adaptation and mitigation (AMCOW, CDKN and GWP, 2012b; Cullis et al., 2018). Africa has only developed one tenth of its hydropower potential, which is less than other regions of the world (AMCOW,CDKN & GWP, 2012b). Agriculture is likely to remain the greatest consumer of water as the demand continues to grow with population expansion (UN-Water, 2018). Climate change will likely further increase the water demands of agricultural as increasing temperatures and more variable rainfall reduces crop yields (AMCOW, CDKN and GWP, 2012b; UN-Water, 2018b). In regions that are water scarce, protection measures are required to maintain agricultural production to ensure sustainable urban livelihoods (UN-Water, 2018).

Governments and governance structures tend to have institutional structures whose mandates are along sectoral lines. These often ignore the interdependence of the water, energy and food sectors and the potential impacts these sectors can have on each other (UNU-INWEH, 2013). Holistically managing the security of the water-energy-food nexus takes into account interdependent decision-making and supports sustainability (UNU-INWEH, 2013). In a developing context, such as Africa, challenges such as urbanization and climate change place stress on water resources, which can develop into exponential consequences for the water, energy, and food sectors. By developing stronger links between water resources, and the sectors that are dependent on producing or using those resources, governments can promote better management. Addressing climate change adaptation for the water-energy-food nexus requires consideration of the impacts and dependencies beyond a sectoral focus, promoting synergy and co-benefits (Rasul and Sharma, 2015b).

Urban Water Resilience

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). In the context of providing urban water security and resilience, cities are complex systems, and are vulnerable to both climate and socio-economic changes. As a result, their vulnerability to stressors, of which climate change is only one, cannot be analysed in isolation.

City solutions often need to be sought at a local scale, although city problems can be caused by non-city-scale phenomena (Arrighi et al., 2016). Decision support based on a city-centric water system can promote integrated adaptation approaches that coordinate between different sectors and different spatial scales (i.e. local, national and regional). Cities are both dependent on and impact on their regional watersheds. Hence ensuring water security for a city will require planning measures to be implemented at a watershed scale to safeguard the supply of upstream and downstream users and not only be focused on measures within the city boundaries.

The sub-systems of a city include the physical and natural environment that are lived in 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 helps them to better manage risks. However, the interdependency of the sub-systems also makes cities vulnerable when one of the systems fails (Arrighi et al., 2016; Cullis et al., 2015).

Co-exploration and Adaptation

Co-exploration has been proposed as a collaborative approach for cities 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; Willyard, Scudellari and Nordling, 2018).

The co-exploration model shifts away from traditional approaches where knowledge for users is created by experts, towards that of research being undertaken with, instead of for, the society under study (Kemp, Fairhurst and Tarryn, 2011; Arrighi et al., 2016). Through the 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 & Walker, 2016).

Top-down versus Bottom-up

Adaptation decision support methods provide an analysis of how decisions can be made between different options (Taylor et al., 2017). These approaches to system impact assessments can be generally characterised as 'top-down' or 'bottom-up' (see Figure 1). 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). 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 scale 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 insights of this technical brief build an understanding of how missing climate knowledge that is needed for decision support can be co-produced for local city planners and scientists (Willyard, Scudellari and Nordling, 2018).

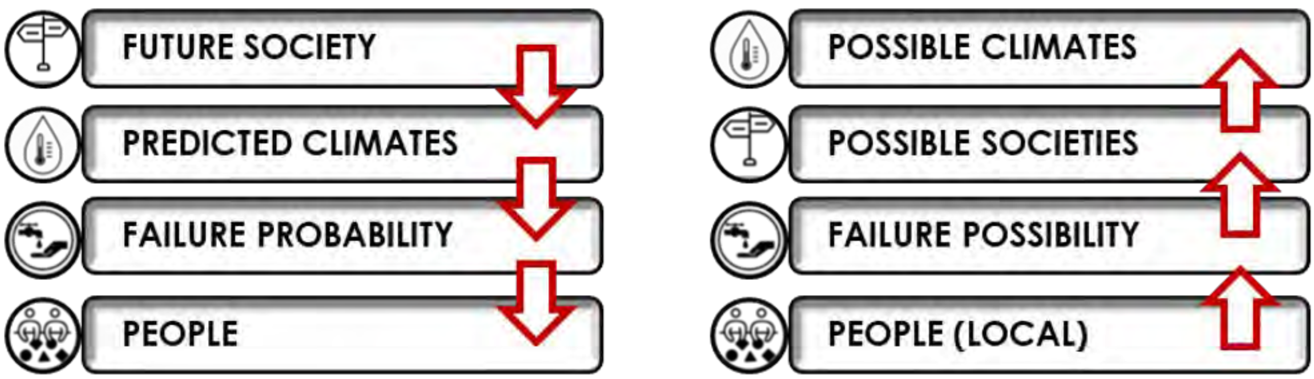


Figure 1 | Simplified steps for top-down (left) and bottom-up (right) adaptation approaches

METHODOLOGY

Exploring Urban Water Resilience

For this study, the definition of resilience was based on the work by Johannessen and Wamsler (2017).

Three levels of resilience to the urban water system were integrated into the process of co-exploring city solutions to climate vulnerability:

- 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).

Urban water resilience was explored using a bottom-up adaptation approach focussed on decision support. Decision-Scaling (DS) was the approach used to analyse which decision options are resilient to a range of futures (Taylor et al., 2017). The approach connected the bottom-up process of co-exploration with the top-down process of incorporating climate and socio-economic information to investigate the risks for water supply to the City of Lusaka. Information on critical water security issues were explored during a series of City Learning Labs held with key city stakeholders. The results from these Learning Labs were analysed using both a city-centric water resources model for the city of Lusaka as well as a larger city-regional model of the Kafue Basin to include the risks to other water dependent sectors.

There are several advantages to the application of the DS framework:

1. 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.
2. 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).
3. It 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 helped to minimize the decision consequences of an uncertain future, and promoted informed decision-making processes facilitated by bottom-up discussion. Synthesis of the analysis was valuable when exploring potential adaptation solutions either as part of the Lusaka Water Security Initiative (LuWSI) or through the development of policy briefs for water supply to Lusaka (FRACTAL and LuWSI, 2018).

Lusaka Water Supply Case Study

Location of the Study Area

The focus city for this research was the city of Lusaka, Zambia. The aim was to investigate adaptation decision-support using co-exploration and a city-centric regional water system within the Kafue River Basin (Figure 2). The study area 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.

Water Supply for the City of Lusaka

The Lusaka Water and Sewerage Company (LWSC) manages the formal water supply to the city of Lusaka. The formal water supply is from

Figure 2 | The Kafue River Basin showing the extent of the study area (WWF, 2003)

the Kafue River and the Lusaka groundwater aquifer, and is treated at the Iolanda water treatment works (see Figure 3).

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 several sources (see Figure 5).

Figure 3 | Iolanda water treatment works Lusaka Zambia

At present, Iolanda has water rights to abstract 200,000 m3/day from the Kafue River. It currently has a design throughput of 110,000 m3/day. However, the age of facilities makes the working ratio of the water plant approximately 95,000 m3/day (JICA, 2009; Millennium Challenge Corporation, 2011). Demographic changes in the city of Lusaka such as population growth and the urban and peri-urban distribution are important influencers in the future resilience of water supply since they determine the socio-economic living conditions of the population.

In addition to the surface water abstracted from the Kafue River, LWSC abstracts groundwater from the Lusaka aquifer which covers an area of approximately 300 km2 with a total of 72 boreholes in operation, of which 10 are large production boreholes (Japan International Cooperation Agency, 2009). The low 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 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 significant number of peri-urban areas within the city of Lusaka mean that the informal options for water supply need to be taken into consideration. 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 climate. 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 (e.g. water kiosks, see Figure 4) 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 m3/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. The majority of the water trusts lack formal systems for the monitoring of the groundwater that they abstract their supply from.

Figure 4 | Water kiosk in Kanyama peri-urban area

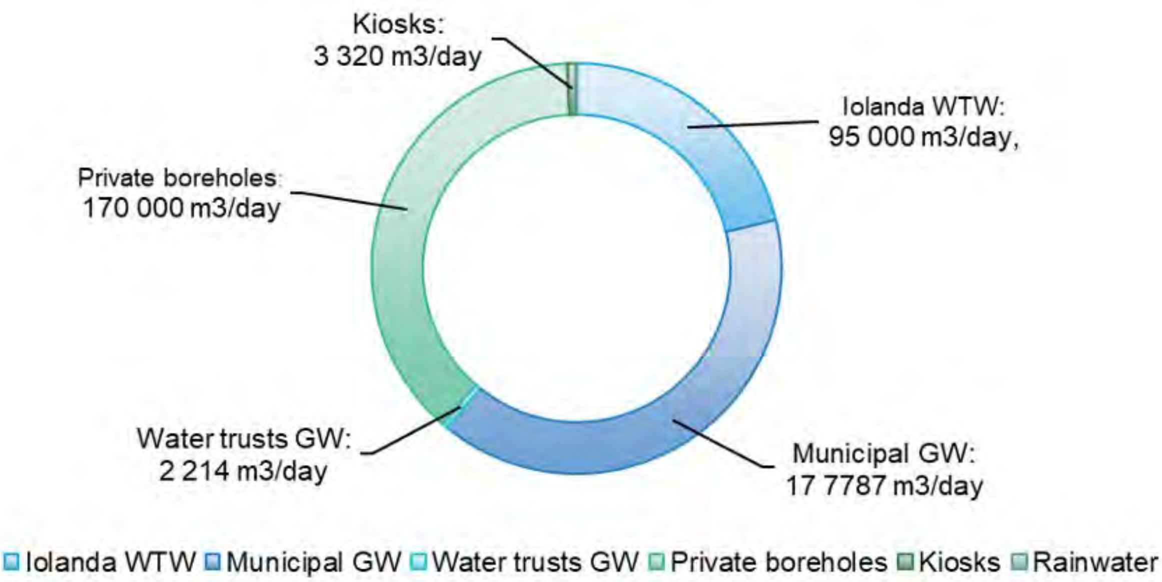


Figure 5 | Baseline supply distribution for urban and peri-urban Lusaka

Surface water from the Kafue River, specifically from the Kafue Flats, has been identified as a major source for potential future water 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 opposed to a resource constraint.

The Water-Energy-Food Nexus

The Zambian 7th National Development Plan (2017-2021) highlights agriculture and energy as growth sectors for Zambia. Nearly 50% of these sectors fall 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 sectors, in order to meet demands without compromising sustainability (Rasul and Sharma, 2015b).

The Kafue River Basin is key to 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). 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). The Kafue Flats is one of the closest water resources for the agriculture that is transported to Lusaka for consumption.

Climate Change Risk and Vulnerability

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; Walker et al., 2018). The predicted higher temperatures in the region, and 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).

In Lusaka 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; maintaining the health of the Kafue River; managing urban flood risks; and providing 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.

Decision-Scaling Approach

For this study an adapted version of the DS framework was used that was derived from the approach by Poff et al. (2015). The adapted framework included other system stressors, in addition to climate change, such as socio-economic stressors to test the system sensitivities and assess the performance of proposed adaptation measures 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).

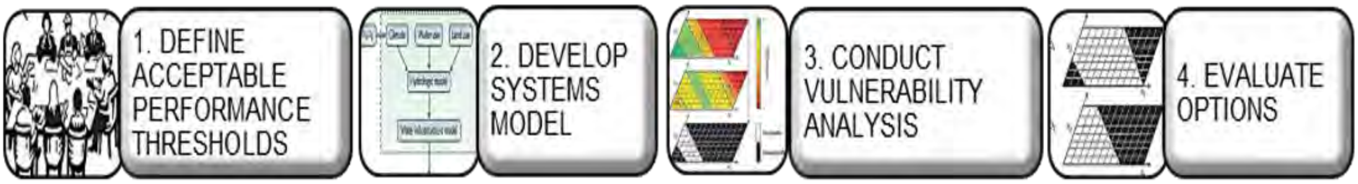


Figure 6 | Decision-scaling framework used adapted from Poff et al (2015)

DS was adopted as a way to holistically explore the water resource risks and 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, DS can meet both social and ecological needs as a robust method of sustainable water resource management for an uncertain, complex future. The thinking behind DS 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 valuable 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.

The DS approach considers a system's resilience in the context of stakeholder-defined needs (Poff et al., 2015). This includes both climate and non-climate stakeholder-defined vulnerabilities or "breaking points" in the performance metrics of the system and then considers adaptation options that perform robustly for a wide range of future scenarios against the specific performance metrics. The framework identifies climate changes as 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 applied in this study and are used to find a possible "safe space" in which decisions can be made. The framework promotes the use of climate adaptation designs that can be flexible, robust and efficient.

There are four stages to the DS framework as shown in Figure 6. The first three stages pertain to risk assessment and the fourth stage pertains to risk management. The DS 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.

Step 1: Defining Acceptable Performance Metrics

The first step in the adapted framework was to gain a better understanding of the current situation with regards to water supply for Lusaka, to identify key climate risks and to determine the appropriate performance metrics for analysis. The Learning Labs held in the city of Lusaka were stakeholder engagements used to define their interests, acceptable performance metrics and shared knowledge (Willyard, Scudellari and Nordling, 2018). Learning Labs 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 Learning Labs are encouraged to share their opinions and needs (Polk, 2015; Arrighi et al., 2016).

The city Learning Labs were used as a platform to find the critical issues faced by a group of stakeholders in Lusaka. 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.

Step 2: Developing a Systems Model

The second step in the DS framework approach is to develop an appropriate system model, or models, based on the improved understanding of the key issues, risks and performance metrics that would aid in decision-making for improved water security.

The models that were developed allowed the exploration of demand and supply options to balance both environmental and development goals through the development and assessment of a variety of scenarios that represented possible futures for Lusaka's water resources considering both local (i.e. city level risks) as well as regional risks.

The Water Evaluation and Planning Tool (WEAP) was chosen as the primary tool to model potential changing responses of the water system to climate change effects in the city of Lusaka (www.weap.org). WEAP is an integrated water resources planning tool used to represent current conditions in a specified area. WEAP has been used previously for modelling the climate change risks for the Zambezi basin (Cervigni et al., 2015).

In order to apply the bottom up DS framework for understanding water security risks for Lusaka two WEAP models were developed. The first was a simple model of just the water supply system to Lusaka integrating both surface and groundwater supply options. The second was an expanded city-region water resources model that also included critical parts of the Kafue River basin that impact on both water and energy availability for Lusaka.

City Model for Lusaka

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. The city model focused on the demand analysis for hydropower demand (inclusive of reservoir evaporation), irrigated agriculture and urban demand as these are currently the greatest demands from the Kafue Flats (WWF, 2017). The city-scale model (Figure 7) was developed first and focussed on the Lusaka water system independently of regional factors. This allowed for the evaluation of impacts confined to the city context. Inputs from the Learning Labs were key to developing this model as they it focussed on what was most important from the perspective of the city decision makers.

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.

City-Regional Model for the Kafue Flats

The greater city-regional model (Figure 8) was a second model developed to integrate the city-centric model into its Kafue basin context. This model accounted for regional co-dependencies to the water system such as hydropower and agriculture. The city-regional models 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. With the difference in model inputs being the inclusion of groundwater supply; 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. Other agricultural, domestic

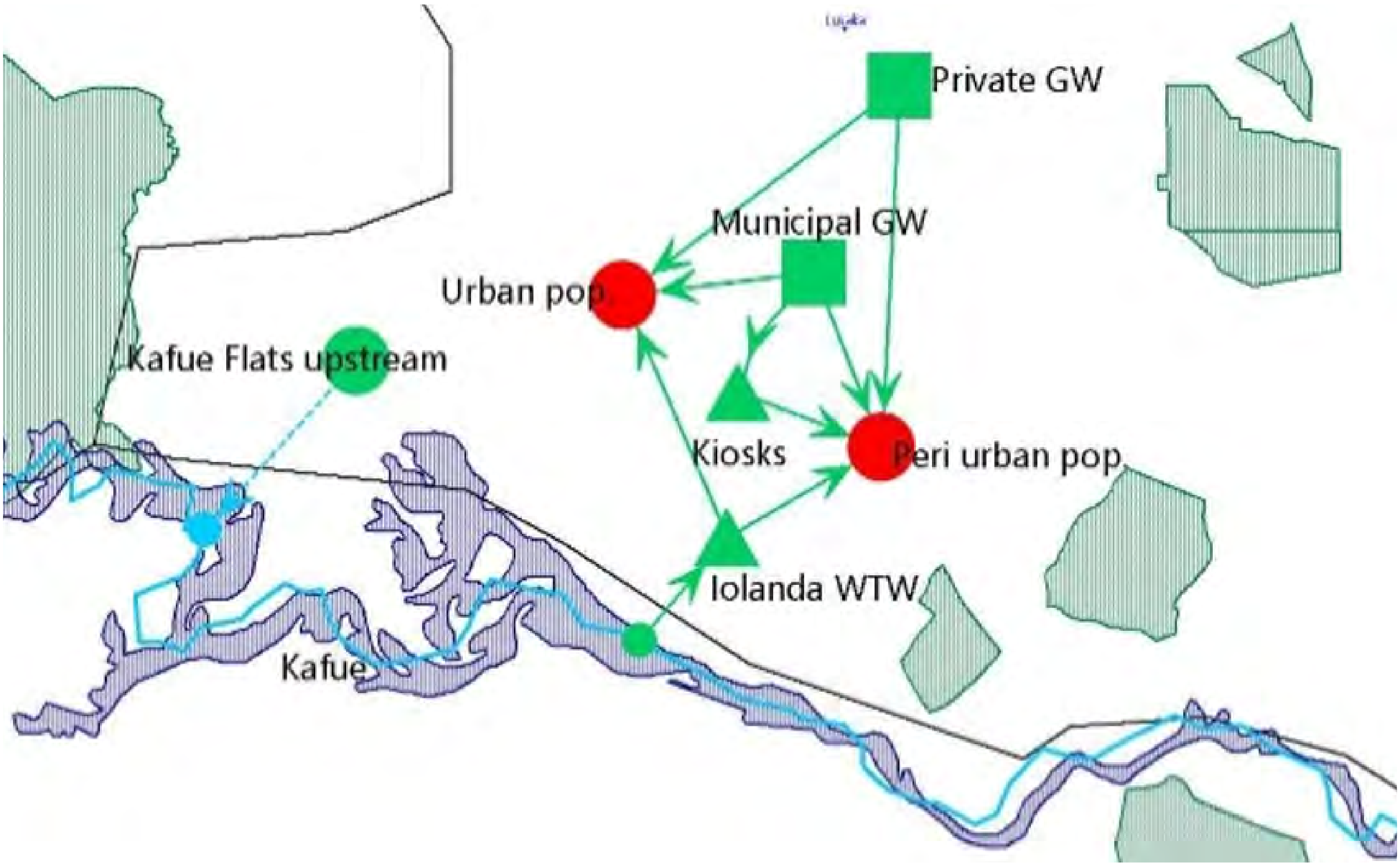


Figure 7 | City scale WEAP model

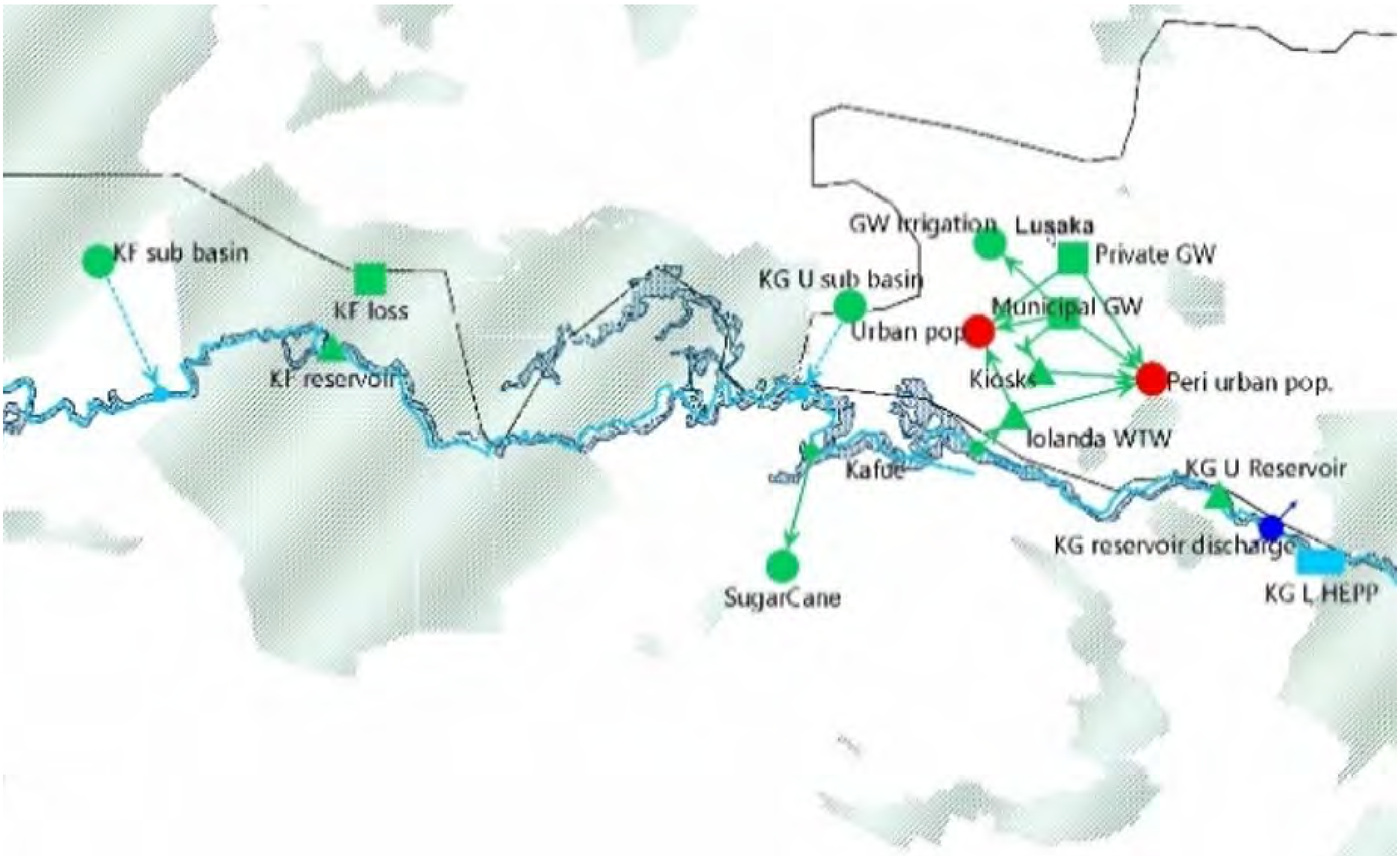


Figure 8 | City-Regional WEAP model

and industrial use within the Kafue flats were assumed negligible in comparison to that for hydropower demand, Zambia sugar and the city of Lusaka (The World Bank, 2010; Spalding-Fetcher et al., 2014).

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), was used as a data input for modelling the water resource system. The runoff outputs from the ZDSS model give surface inflow inputs for the Kafue River near the city of Lusaka. The advantage of this data source was that it had already been tested against observed historical flows at streamflow gauges.

The ZDSS model also allowed for the extraction of the underlying precipitation, temperature, and evaporation data. When integrating critical climate change information into the planning of urban contexts, the different temporal and spatial scales were considered depending on the specific water infrastructure. For the purpose of this study, a monthly water resources model was appropriate.

Step 3: Conducting a Vulnerability Analysis

The third step is to test the sensitivity of the system to identified critical climate and non-climate stressors and determine the vulnerability of the systems in terms of the critical performance metrics.

A system's vulnerability to changes can be explored by way of a stress test against the key performance metrics (García et al., 2014; Steinschneider, Mearns and Brown, 2015). Water supply stress tests identify 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 was repeatedly run, for multiple climate and socio-economic changes, these potential changes were named as system stressors. The risks associated with the supply included climate changes. 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 manner in which the water resources are distributed (Ray and Brown, 2015).

Demand side pressures can include, but are not limited to, population growth, urbanization, a shift in agricultural and irrigation patterns, or increased environmental water demands.

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.

The system's performance against stressors was 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. Three dimensions were used for the stress test, namely: climate stressors, non-climate stressors and management actions.

Climate Stressors

Climate stressors considered directly relevant to city stakeholders were included. Based on the co-developed outputs of the city learning lab different climate stressors were relevant at the city and the regional scale based on the dominant water supply sources to the urban centre of Lusaka, the hydropower plants and the Zambia Sugar irrigation scheme. Since 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, for the city-centric model, local changes in mean annual precipitation (MAP) over Lusaka and regional changes in mean annual runoff (MAR), upstream of the Lusaka abstraction off

Table 1: 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%

Table 2: Isolated regional-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%
Upstream change in Temp.	Evaporation is a function of temperature and affects the reservoir storage volume and the irrigation demand (on a mean monthly basis)	0°C to 3°C

the Kafue River were chosen as the climate system stressors that would have vulnerability risks for the Lusaka water system. These are summarised in Table 1. The range of these climate stressors was intentionally variable to not limit the extents of the risk map.

For the city-regional model of the Kafue Flats, the alternative climate futures considered a hotter future from an increase in temperature, and both a wetter and drier climate, from changes in mean annual precipitation over the Kafue Flats region (see Table 2). Historical climate data from the 1960s-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.

Non-Climate Stressors

Planned demographic and water use changes were used as non-climatic socio-economic stressors to the water supply system. At a **city scale** these included (see Figure 9):

- 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: 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).

Figure 9 | Demographic and water use changes for water supply system stressors

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).

At a **city-regional scale** these included:

- 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 provide 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).

Management Actions

A management actions scenario approach was used for the development inputs into the model. These management actions were either on a city or a city-regional scale and considered socio-economic development futures (excluding socio-economic stressors of population growth and distribution which were included under the non-climatic stressors).

The proposed management actions did not account for the associated shut down time that would be required for the increased capacity of the formal water supply systems. They also assumed that the water received from the proposed development was of adequate quality. Each proposed management action, based on the Water Supply Investment Master Plan (see Table 3), was independently set up and run.

Sector development plans (Government of Zambia, 2017) were used as a basis for determining future water use and demand in the city-regional scale model, which focused on water demands for hydro-power, and irrigation (Chomba and Nkhata, 2016). Table 4 outlines the proposed development at a city-regional scale. The development included the proposed expansion to irrigation and hydropower.

Sugar is a major crop in the Kafue Flats and the largest irrigation scheme in Zambia is located there. The irrigation expansion was based on the Multi Sector Investment Opportunities Analysis (MSIOA) study by the World Bank (The World Bank, 2010), which highlights likely irrigation upgrade projects and the maximum theoretical potential for irrigation. The existing

Table 3: Proposed management actions for Lusaka city-scale water supply (JICA, 2009; Gauff Ingenieure, 2013)

MANAGEMENT ACTIONS	DESCRIPTION
Upgrade Kafue Pipeline	Upgrade Kafue Pipeline to 320 000 m^3/day total by 2017 (P1) Upgrade Kafue Pipeline to 480 000 m^3/day total by 2020 (P2); and Maximise abstraction capacity to 640 000 m^3/day total by 2035 (P3)
Increased boreholes	130 000 m^3/day total by 2010; 180 000 m^3/day total by 2017

Table 4: 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-Fletcher et al. (2014)

hydropower dam releases from Itezhi-Tezhi to Kafue Gorge Upper help to limit the seasonal variability for sugar cane irrigation (Chomba and Nkhata, 2016). Three irrigation management actions were identified and modelled: existing irrigation (I1), a short-term upgrade (I2) and a long-term upgrade (I3).

The hydropower management actions (H1 and H2) 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.

The city-regional-scale scenarios were based on the 2035 city-scale scenario (P3); as this was the most realistic decision-making time frame. This assumed that all the socio-economic stressors and management actions of the 2035 city-scale scenario have been implemented. The risk analysis looked at scenarios that combined management actions and the climate and socio-economic stressors; these are conceptually shown in Table 5 for both the city scale and the city-regional basin scale model. At a city scale the stress test considered three city-scale scenarios (i.e. P1, P2 and P3); while at city-regional scale five scenarios were considered using the long-term city-scale scenario (P3) as the base socio-economic case (i.e. P3H1, P3H1I1, P3H1I2, P3H1I3, and P3H2I3).

To provide current-day context on the risks associated with the use of historical climate and climate variability in the model, data from the Climate Research Unit (CRU) (Harris et al., 2014) was used. This showed where recent El Niño/Southern Oscillation (ENSO), La Niña, and the 2014-2015 mean precipitation and temperature plotted on the risk map. For each risk map, precipitation variability is represented on the x-axis and the other climate variable (i.e. mean annual runoff variability in the case of the city-scale model or temperature in the case of the city-regional model) is represented on the y-axis.

Table 5: Water demand management scenarios

SCALE	SCENARIOS	SOCIO-ECONOMIC STRESSORS	CLIMATE STRESSORS	MANAGEMENT ACTIONS
CITY	P1 (2017)	See Figure 4.7	City-scale (∆ regional MAR and ∆ 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 (∆ regional temperature and ∆ 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

Step 4: System Evaluation

The framework identified potential stressors that could result in risk and then identifies the likelihood of said climate changes using projections. The water supply stress test is based on system performance metric "breaking points". This system evaluation helps to identify the "safe space" where decisions can be made.

Estimating the risk of the exceedance 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 capable of changing the spatial resolution of the projections (Grijsen et al., 2013). 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.

Highlighting the opportunities and risks for the city of Lusaka within the Kafue Flats is important for public and private sector decision makers in the water management sector. The risks are both climate and socio-economically driven, and the impacts require trade-offs. These risks can be investigated with the use of narratives (Jack and Jones, 2019), which look at the nature and potential extent of these risks at a city and regional scale. The management actions outlined were analysed using the city-regional WEAP models for Lusaka and the Kafue Flats. By quantifying the modelled vulnerabilities, it was possible to identify the climate and socio-economic stressors to a city-regional water system, and see how the city-regional sensitivities and uncertainties translate into city-centric impacts.

Table 6: Risk definition for performance metrics of 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.

DS uses the risk definition to inform decisions instead of identifying risks from climate projections. The risk definition of the performance metrics (Table 6) shows the risk levels at which domestic and irrigation water demand are met, and the generation and reliability of hydropower. This ensured that the performance metrics accounted for the water-energy-food nexus. The risk levels obtained from the results were attributed to a combination of climate, socio-economic stressors and management action system stressors. Both high and severe risks were considered unsustainable for the water system. Critical to all the risk maps produced was not so much the qualitative values of the performance metrics but the associated level of risk the created for the Lusaka water system. This valued the process of developing the risk map and understanding the information required to identify vulnerabilities and trade-offs over the product of the Lusaka water model itself. The value in this made the process applicable in contexts where reliable data may not be available and allows for the risk analysis process to be simplified for several contexts.

RESULTS

Lusaka City Learning Labs

The city Learning Labs provided a platform for stakeholder engagement and to assist in determining the critical issues and relevant performance metrics of the Lusaka water system. The Learning Labs facilitated collaboration between researchers, university partners, city officials and civilians. Through the learning labs burning issues were identified and discussions were had on how these issues could be better managed and less vulnerable to climate variability in the future.

A key output of the Learning Labs was developing the system model through co-production with stakeholders to map the water system and the associated decision-making frameworks. These exercises mapped out actual and perceived causes of the issue of water supply and aimed to better understand city systems and climate information needs. They also outlined main sources of supply and demand priorities (Figure 10).

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.

The Learning Labs were also valuable for developing a better understanding of how the existing infrastructure works. The Labs 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

Figure 10 | Co-produced mind mapping to inform systems model

water abstraction and treatment plant. It 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.

During the Labs stakeholders were given an opportunity 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, namely: Water Supply, Groundwater Pollution, Groundwater Levels and Flooding. The Water Supply thematic group focused 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 (Figure 11).

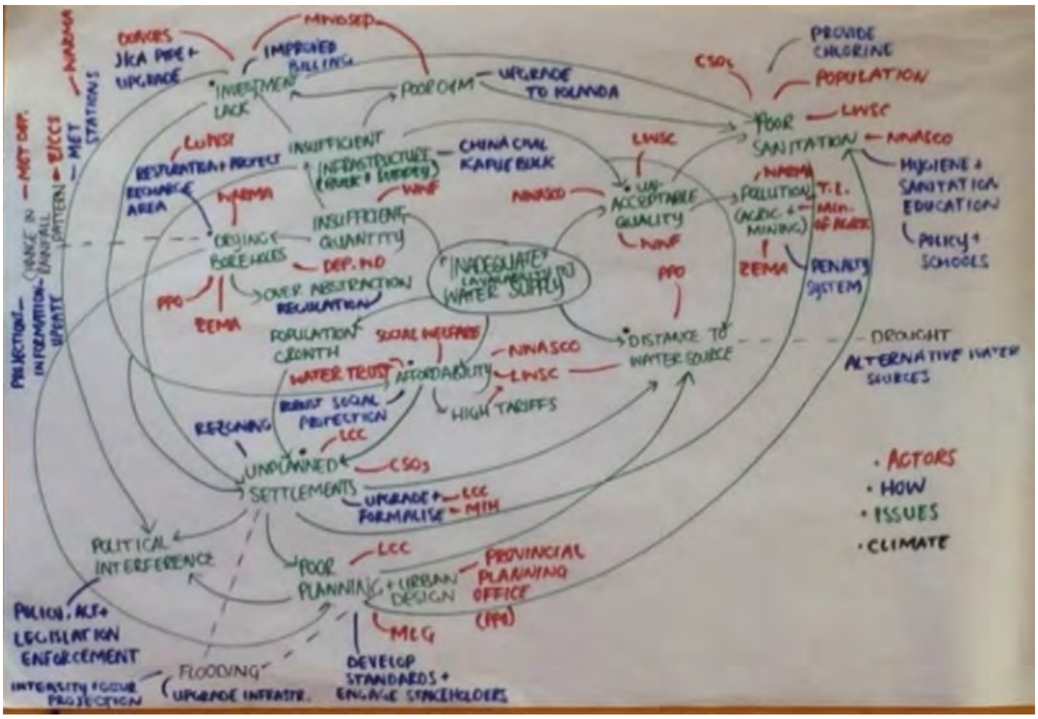
Risk definitions were based on potential vulnerabilities identified during discussions in the Learning Labs. From these key risk areas, we were able to highlight key sectors (i.e. water, energy and food) and the relevant metrics for their performance, namely:

- domestic water demand being met,
- irrigation water demand being met, and
- hydropower generation and reliability

Learning Labs aimed to fill the gap of missing local knowledge regarding the city-centric water system complexities rather than relying on external estimates which could be biased (Willyard, Scudellari and Nordling, 2018). This is valuable especially in cases where there is limited to no data, which is often evident in the developing context. Continuous engagement on articulating and discussing the dynamics of the water resource system and the competing interests within it, showed the complexities of water systems and their co-dependent sectors of energy and food.

Learning Labs were invaluable for gaining feedback on the city-centric and city-regional models of Lusaka and the Kafue flats' and to present the results of the vulnerability analysis. The Learning Labs unpacked the assumptions made and how they were informed as well as

Figure 11 | System issues, actors and climate drivers



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. In addition, the learning lab process empowered the stakeholders to take ownership of their understanding of how climate information could be incorporated into the decision-making process.

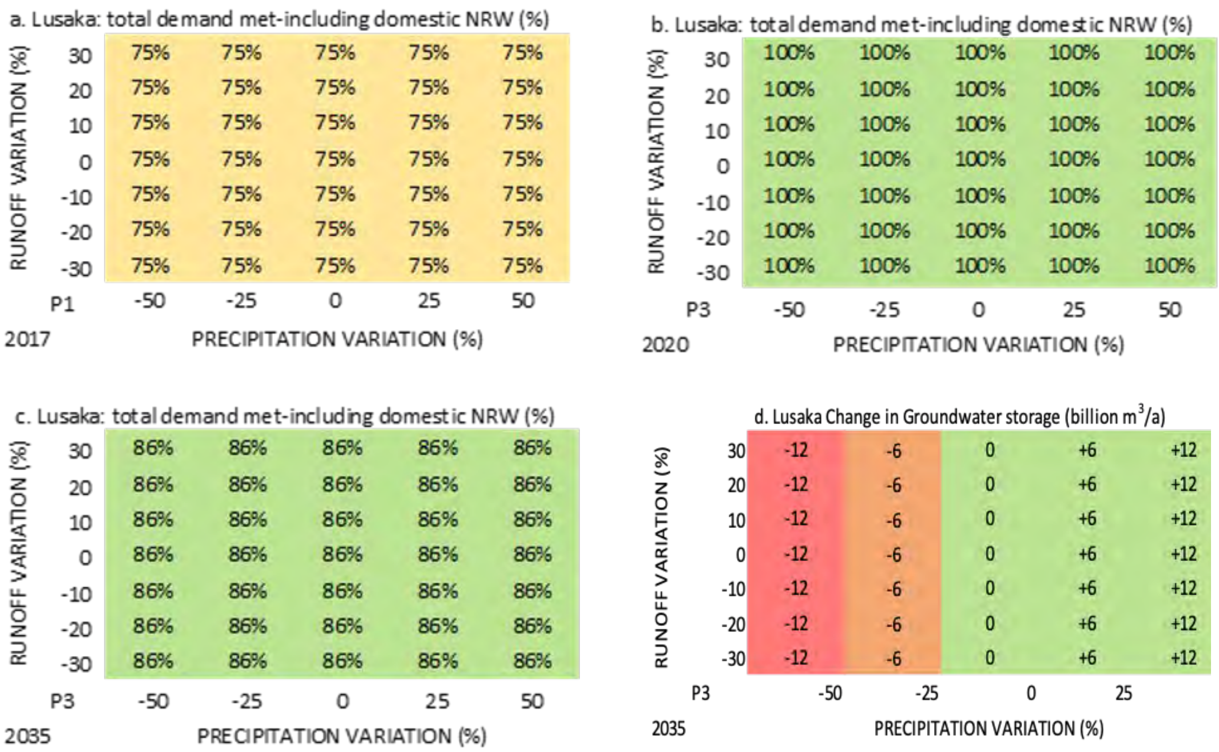
Decision-Scaling Risk Analysis

City-scale risks and responses

The city-scale risk map looked at the 2017, 2020 and 2035 total domestic water demand met (inclusive on non-revenue water); and city-scale relevant climate variability (variations in runoff and precipitation). This scenario identified 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 actions (e.g. increased infrastructure capacity). Figure 12(a)-(c) shows the risk maps for three scenarios. 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). Under historical climate conditions, the baseline (P1) city-scale risk map (Figure 12a), shows 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. Figure 12b (P2) showed an ideal scenario in which all water demand was met, however the P3 2035 scenario (Figure 12c), was used as the baseline on which to develop the Kafue Flats city-regional scale scenarios, as it was a more realistic planning horizon.

Figure 12 | Risk map under (a) P1, (b)P2, (c) P3 development and (d) change in groundwater storage



In addition to the three scenarios a fourth risk map was produced (Figure 12d) to measure change in groundwater storage. Lusaka's water supply is vulnerable to climate based on the quantity of water available for abstraction (i.e. Kafue River MAR) and the quantity of precipitation available for groundwater recharge (i.e. regional MAP). Since groundwater recharge was proportionate to changes in precipitation the groundwater risk map was only produced for the city-centric scenarios.

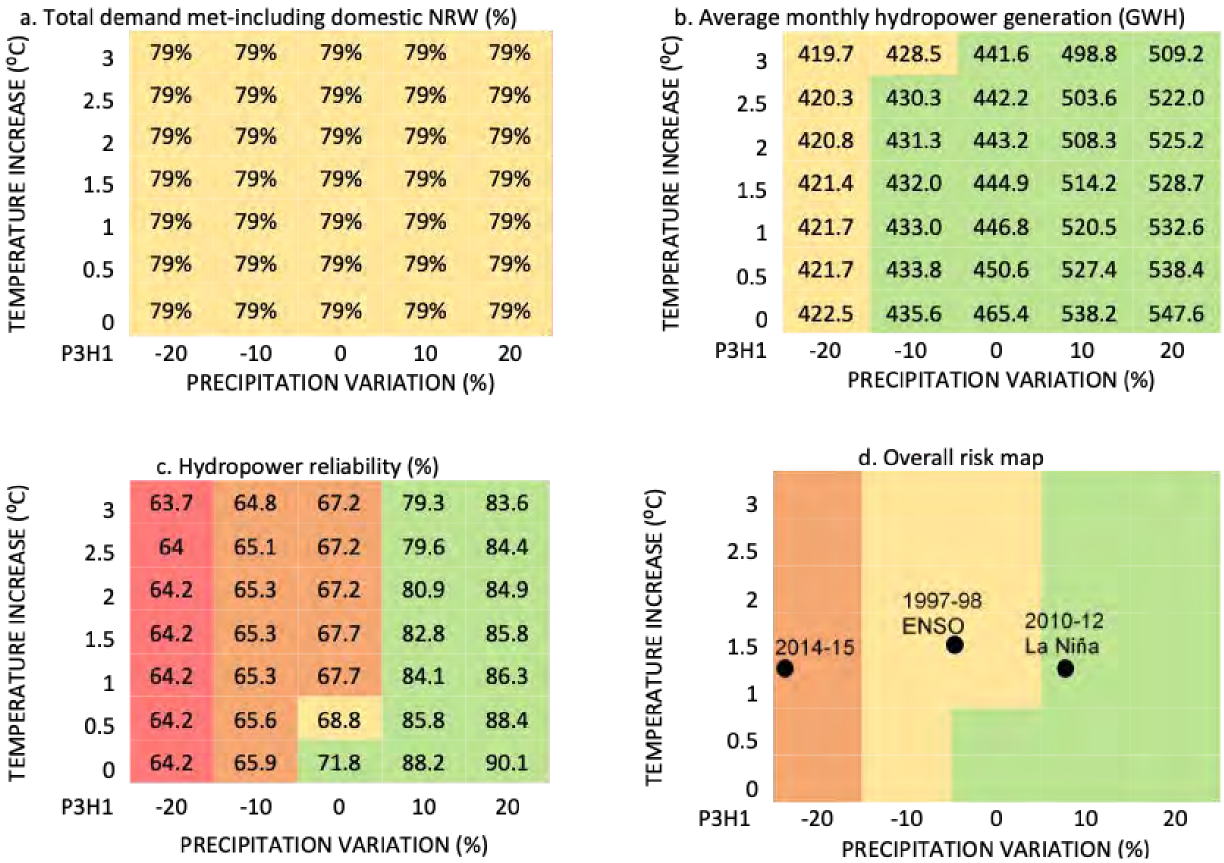
Regional-scale risks and responses

The baseline city-regional scale risk maps (Figure 13) accounted for climate variability at a regional-scale and the proposed management actions for Kafue Flats regional water supply (Table 4).

Baseline 2035 development Scenario

The baseline domestic 2035 development altered the risk status of the isolated city-scale model (Figure 13a). As an isolated city-scale model the domestic water demand met indicator (Figure 12c) was a low risk (86%), but within the city-regional model this risk marginally moved into the medium risk (79%) (Figure 13a). The demand met indicator varied negligibly over all the regional-scale 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 13b) was mostly a low risk, except in the case of average precipitation decreasing by 20%. Although the average monthly generation was low risk, the hydropower reliability (Figure 13c) indicates 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 13 | 2035 baseline (P3H1) development city-regional risk maps



The overall risk map for the P3H1 scenario (Figure 13d) shows that for the 2035 baseline development scenario the climate stressor which left the system most vulnerable was changes in precipitation. An increase in average precipitation had an overall positive effect for all sectors considered, however the plotted recent climate averages for the 2014-2015 period in Figure 13d show that the city has recently been at high risk. The 2014-2015 period was also during the most recent drought, for which Learning Lab participants did refer to power shortages during that time.

Hydropower development Scenario

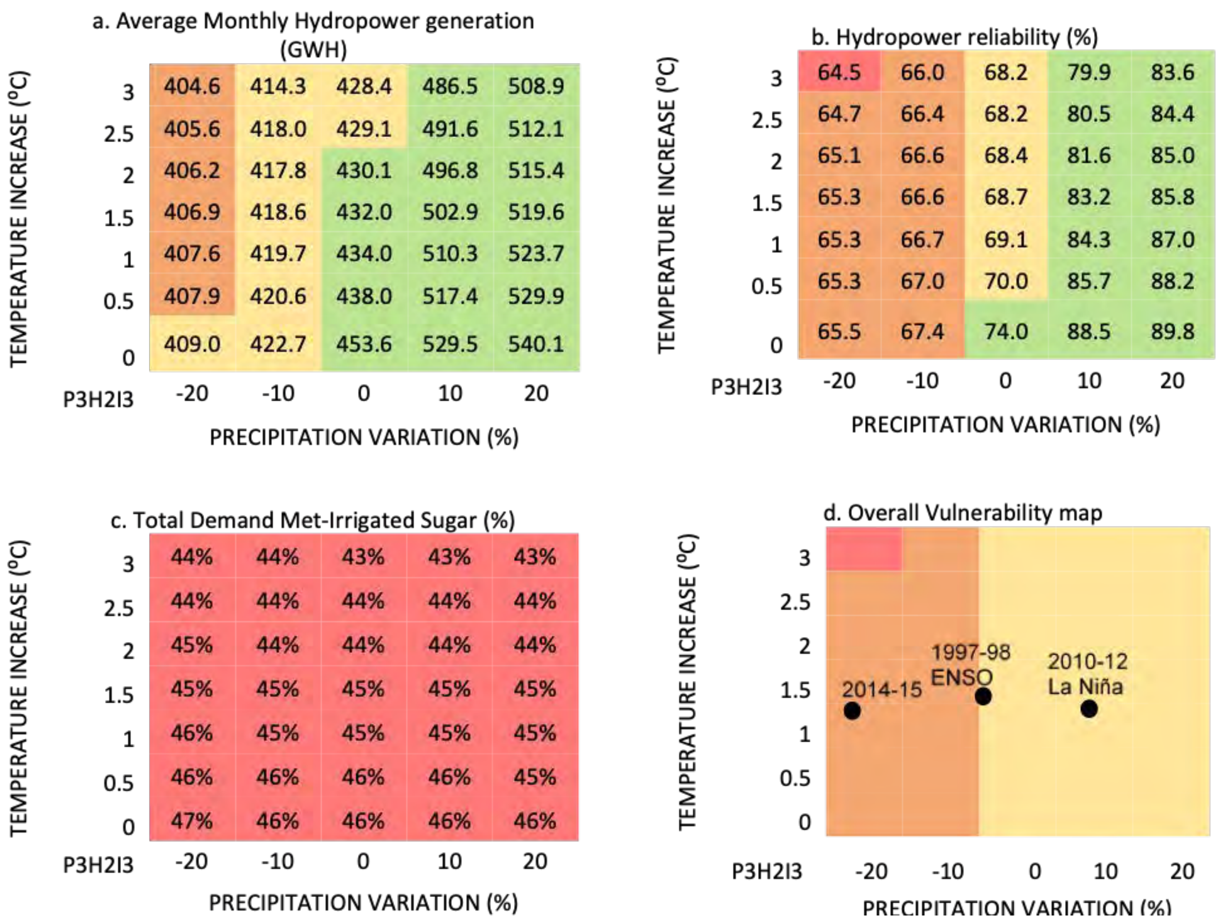
The average baseline hydropower generation at Kafue Gorge Upper is 465.4 GWh/month in comparison to the 1993-2012 monthly generation of 430 GWh (Spalding-Fetcher et al., 2014). The generation at Kafue Gorge Upper was not greatly affected by warmer and drier climates in terms of generation, but its reliability was 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 14b) in comparison to the baseline 2035 development P3H1.

Because the hydropower development scenario was based on the full irrigation development scenario, the total irrigated demand met for sugarcane (Figure 14c) is the same as that for the P3H1I3 scenario (Figure 17c). The average monthly hydropower generation shown (Figure 14a) is only for Kafue Gorge Upper hydropower plant. Based on the overall risk map (Figure 14d) 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.

Irrigation development Scenario

The impact of an increasing irrigation area

Figure 14 | Full development (P3H2I3) scenario city-regional risk maps



is that it increased the overall demand requirement from the Kafue river. In the case of the Kafue flats and the Kafue Gorge hydropower scheme, the change in irrigation area had minimal impacts on the generation or the downstream discharge (Figure 15). Increasing irrigation reduced the average hydropower generation (Figure 15a-c) 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 17), there may be water abstraction that is unregistered.

For the hydropower generation and reliability, precipitation variability has more of a risk impact than temperature variability. The average monthly hydropower generation (Figure 15) shows less risk than that for hydropower reliability (Figure 16). The hydropower reliability plots also show that even with no changes in precipitation both the current day (I1), and future (I2 and I3) 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 was a precipitation shortfall modelled, 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 18 a and b) plot the historical climate events (ENSO, La Niña and 2014-2015) 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 18 c), 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 17c). However, if the allocated abstraction for irrigation from the Kafue Flats is not capped at the existing capacity, there is potential for this risk level to decrease.

Figure 15 | Average monthly hydropower generation (GWH) under I1, I2 and I3

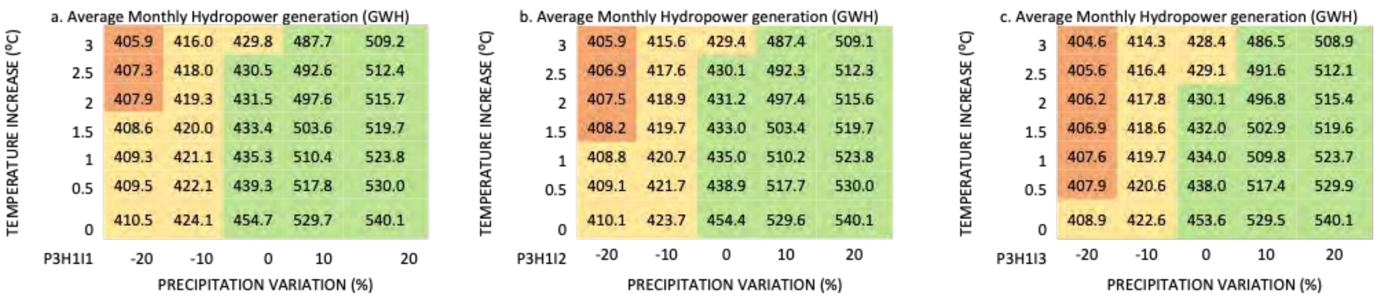


Figure 16 | Hydropower reliability (%) under I1, I2 and I3

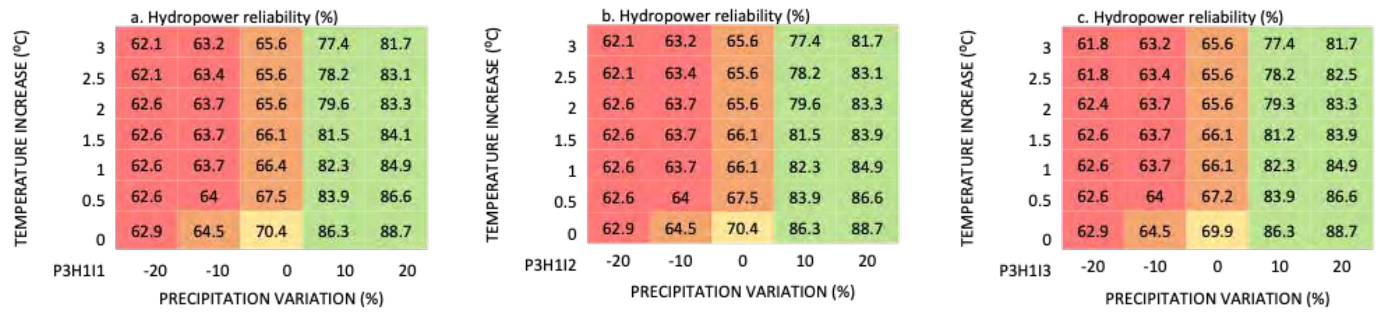


Figure 17 | Total irrigation demand met (%) under I1, I2 and I3

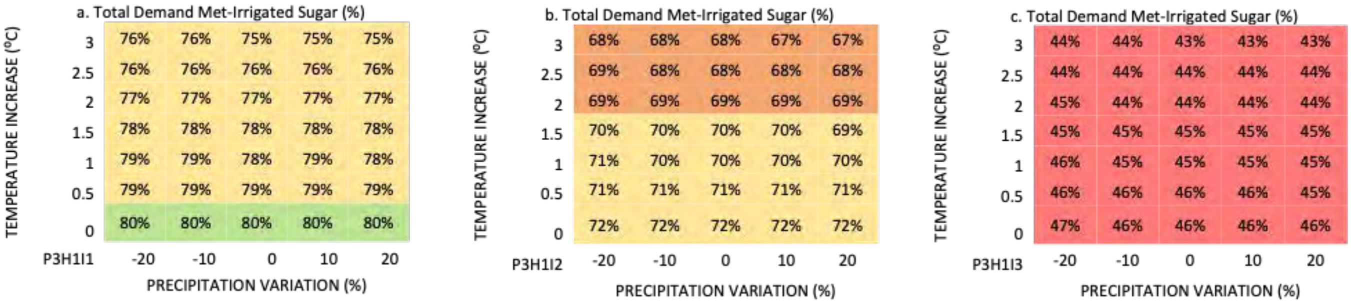
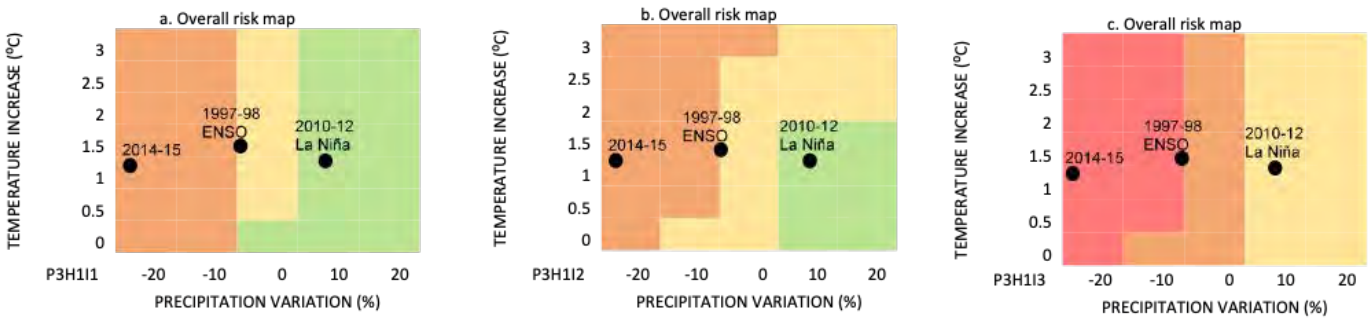


Figure 18 |Overall risk map for irrigation scenario



KEY LESSONS

The benefits of the DS 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.

In an African context, the situation of water supply to the city of Lusaka 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 could have negative impacts on another sector both at a city and at a city-regional scale. As a result, the risks of water resources not being adequately managed in the face of climate changes are shared between the sectors. Within the Lusaka models, allocating the same demand and supply priority to the water dependent sectors allowed for analysis potential trade-offs between these water dependent sectors.

The outcomes of this study identified that the city-centric water system of Lusaka was more vulnerable to socio-economic changes, such as population growth and management of non-revenue water, than climate changes. Whereas the city-regional water system of Lusaka and the Kafue Flats had vulnerabilities to both socio-economic and climate changes.

Climate Change Vulnerabilities

City scale vulnerabilities

The climate stressors chosen for both the city and the city-regional scale models were important in determining the system vulnerabilities. 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 MAR) and the quantity of precipitation available for groundwater recharge (i.e. regional MAP). 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.

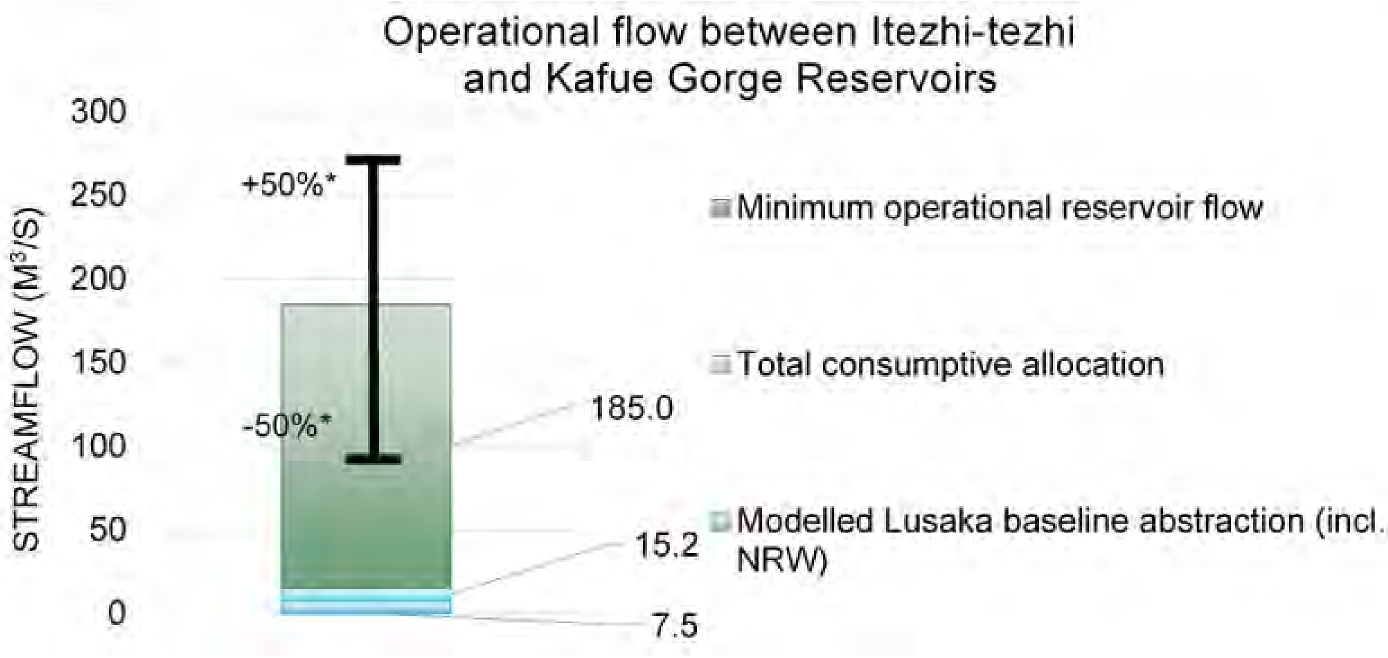
Climate change responses are not explicitly evident at a city-scale for the formal water supply systems (i.e. surface water from the Kafue River). Figure 19 shows operational flow between Kafue reservoirs with the total consumptive allocation (15.2 m3/s) and Lusaka's average baseline abstraction (7.5 m3/s).

The figure also includes the extreme range of predicted changes in runoff for the Kafue River (from -50% to +50%), which indicates that even if streamflow were to be reduced by 50%, Lusaka's abstraction from the Kafue River would still only constitute less than 10% of the minimum operation flow between the Kafue River reservoirs (Fant, Gebretsadik and Strzepek, 2013) This highlights why the city-scale system did not have any evident vulnerabilities to climate stressors as Lusaka's abstraction from the Kafue River is a negligible proportion of the minimal operational flow between Itezhi-Tezhi reservoir and Kafue Gorge Upper (185 m3/s).

At a city-scale, this apparent lack of direct climate vulnerability puts the city in a flexible space as they are able to focus on socio-economic system stressors as key priority areas for water supply. However, informal water supplies (e.g. the peri-urban areas who are more reliant on groundwater supply) are likely to have more direct climate risks as variability in precipitation and temperature are likely to affect groundwater recharge.

If the system is operated to prioritise water supply then there is very little direct climate change risk for water supply, but there is an

Figure 19 | Lusaka's abstraction relative to the consumptive allocation and operational flow between Kafue reservoirs (Gauff Ingenieure, 2013)



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

indirect risk due to the impact decreased streamflow would have on hydropower and energy for pumping and treatment of the water. A possible adaptation option is therefore to provide alternative energy supply as well as more diversified water sources for Lusaka's citizens. Indirect climate vulnerabilities, such as migration from the peri-urban to the urban area which will change the city's demand, as a contributor to water security risk if not water availability risk, should also be considered.

City-regional vulnerabilities

At a city-regional scale, the climate stressors of variations in MAP and Temperature simulated 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.

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

The climate change responses for the city and the city-regional system are being considered in isolation. There is a connection between MAR 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.

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.

Socio-Economic Vulnerabilities

The socio-economic stressors and management actions were linked to the existing development plans as outlined in the case study. Each of the stressors or actions affected the vulnerability of the water system and would have financing impacts and associated timelines. The socio-economic changes that were modelled included the following:

Population

Population at a city-scale was a primary consideration, as African cities are expected to grow considerably by 2050. This change determines how the demand requirement at a city-scale impacts the need for infrastructure to meet that demand. At a city-regional scale changes to population affect the energy requirement from hydropower, the amount of land available for agriculture as communities expand onto fertile land, and the agricultural yield requirements, since Lusaka is a key export for the Kafue Flats (WWF, 2017).

Non-revenue water (NRW)

NRW is a loss of water that could have otherwise been used elsewhere. This change was only applied at a city-scale, where it has the greatest impact on water security. Non-revenue water would be applicable for both irrigation and hydropower at a city-regional scale too but was not applied.

Peri-urban population distribution

The choice to use this as a city-scale socio-economic vulnerability indicator was made because 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 the formalised water system, which often has higher per capita demands.

Water supply infrastructure

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 and they represent current, short term and optimal sugar cane irrigation. The availability of water for irrigation, although influenced by climate, was also greatly influenced by the maximum allocated abstraction. Without an increased allocation the irrigation supply will not be met, hence the severe risk evident in the risk maps for optimal irrigation development (I3).

Hydropower development

Although Zambia's hydropower is distributed via a central grid, and energy produced at Kafue Gorge Lower does not necessarily supply the city of Lusaka, the hydropower generated in this region contributes approximately 50% of Zambia's energy, making its overall production a key factor to consider for water supply and economic development.

Each change potentially poses 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 efficiencies and capacities can handle the increased demand, although this is based on 15% NRW by 2035. City-regional benefits are that increased hydropower production, decreases the water security risk at a city-scale as electricity allows for water pumping. Overarching costs at a city-regional scale are potential water pollution and over abstraction associated with increased irrigation. Another cost is that a greater population would increase their footprint on the existing groundwater aquifer, which would have impacts on groundwater recharge and quality at a city-scale.

At both a city and a 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-requires institutions to work together for implementation and to have a positive impact on the environment in the short and the long term. 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).

Water Co-Dependencies

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. 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.

Although the allocated consumption of 7.5 m3/s for the Kafue Flats (Figure 14) 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. Conversely, 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.

The importance of having power to pump the water to Lusaka is critical and represents the greatest climate change risk for water supply to Lusaka (along with the fact that only a relatively small proportion of the population have access to the formal water supply – which is probably more critical for total water supply risk as households more dependent on local supply. This further highlights the importance of city-regional impacts as at a regional-scale, water is needed 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.

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, because the current power supply is mostly for industrial and domestic use.

A trade-off for water security to Lusaka within the city-regional system was 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. This would then pose a risk to city-scale water supply.

Adaptation Solutions

The advantage of the use of the DS 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. The study's approach favoured the process over the product through engagement with key stakeholders, promoting the use of a learning model based on understanding a system and what it is vulnerable to rather than focussing on quantitative results, and the trade-offs faced in adaptation decision making. This approach made best use of the available information and managed uncertainties.

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. 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 DS framework process. The capacity of the Learning Lab participant stakeholders to implement change in their respective institutions is also limited.

Identifying the key method learnings

The methodology followed in this study produced a learning model 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.

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. 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.

CONCLUSION

Bottom-up adaptive decision-support, such as DS, 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 DS for the water system of the city of Lusaka, Zambia.

The study approach identified system vulnerabilities and unpacked 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. As a 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.

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. 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 an 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 the inclusion of water quality in the modelling process.

REFERENCES

AMCOW, CDKN, and GWP, 2012a. *Water Security and Climate Resilient Development: Strategic Framework.* Abuja, Nigeria.

AMCOW, CDKN, and GWP, 2012b. *Water Security and Climate Resilient Development: Technical background document.* Abuja, Nigeria.

ARRIGHI, J., KOELLE, B., BESA, M.C., SPIRES, M., KAVONIC, J., SCOTT, D., KADIHASANOGLU, A., BHARWANI, S., and JACK, C., 2016. *Dialogue for decision-making : unpacking the ' City Learning Lab ' approach.* Cape Town, South Africa. Available from: https://www.weadapt.org/knowledge-base/urban-adaptation-to-climate-change.

BROWN, C., 2011. *Decision-Scaling for Robust Planning and Policy under Climate Uncertainty.* World Resources Report Uncertainty Series. Washington DC, USA. Available from: http://www.worldresourcesreport.org/files/wrr/papers/wrr_brown_uncertainty.pdf.

BUTLER, D., WARD, S., SWEETAPPLE, C., ASTARAIE-IMANI, M., DIAO, K., FARMANI, R., and FU, G., 2017. Reliable, resilient and sustainable water management: the Safe & SuRe approach. *Global Challenges.* 1 (1), pp. 63–77. Available from: http://doi.wiley.com/10.1002/gch2.1010.

CALOW, R., BONSOR, H., JONES, L., MEALLY, S.O., MACDONALD, A., and KAUR, N., 2011. *Climate change, water resources and WASH: A scoping study.* London, UK. No. 337. Available from: https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/7322.pdf.

CERVIGNI, R., LIDEN, R., NEUMANN, J., and STRZEPEK, K., 2015. *Enhancing the Climate Resilience of Africa's Infrastrucutre: The Power and Water Sectors (technical appendix).* Washington DC, USA: The World Bank.

CHOMBA, M.J. and NKHATA, B.A., 2016. Water Security on the Kafue Flats of Zambia. *Technical Report of the International Water Security Network.* Johannesburg, South Africa: Water Research Node, Monash.

CULLIS, J., ALTON, T., ARNDT, C., CHANG, A., GABRIEL, S., HARTLEY, F., JAGER, G. De, ROBERTSON, G., SCHLOSSER, C.A., and THURLOW, J., 2015. *An Uncertainty Approach to Modelling Climate Change Risk in South Africa.*

CULLIS, J.D.S., WALKER, N.J., AHJUM, F., and RODRIGUEZ, D.J., 2018. Modelling the water energy nexus: Should variability in water supply impact on decision making for future energy supply options? *Proceedings of the International Association of Hydrological Sciences*. 376, pp. 3–8.

FANT, C., GEBRETSADIK, Y., and STRZEPEK, K., 2013. *Impact of climate change on crops , irrigation and hydropower in the Zambezi River Basin.* Helsinki, Finland: United Nations University. No. 039.

FRACTAL and LUWSI, 2018. *Policy Brief | Lusaka Water Supply and Sanitation*. Lusaka, Zambia. Available from: http://www.fractal.org.za/wp-content/uploads/2019/09/Policy-Brief-Lusaka-Water-Supply-web-version.pdf.

GARCÍA, L.E., MATTHEWS, J.H., RODRIGUEZ, D.J., WIJNEN, M., DIFRANCESCO, K.N., and RAY, P., 2014. *Beyond Downscaling: A Bottom-Up Approach to Climate Adaptation for Water Resources Management.* Washington DC, USA: The World Bank.

GAUFF INGENIEURE, 2013. *Lusaka Water Supply, Sanitation and Drainage (LWSSD) Project.* Nuernberg, Germany. Available from: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3852305&tool=pmcentrez&rendertype=abstract.

GODET, F. and PFISTER, S., 2007. *Case study on the Itezhi-tezhi and the Kafue Gorge Dam. The science and politics of international water management*. Part I and II (April).

GOVERNMENT OF ZAMBIA, 2017. *7th National Development Plan 2017-2021*. Lusaka, Zambia: Ministry of National Development Planning. Available from: http://www.mndp.gov.zm/download/7NDP.pdf [Accessed 23 February 2018].

GRIJSEN, J., BROWN, C., TARHULE, A., GHILE, Y., TANER, M., TALBI-JORDAN, A., DOFFOU, H.N., GUERO, A., DESSOUASSI, R.Y., KONE, S., COULIBALY, B., and HARSHADEEP, N., 2013. Climate Risk Assessment for Water Resources Development in the Niger River Basin Part I: Context and Climate Projections. In: *Climate Variability - Regional and Thematic Patterns.* Amherst, USA: InTech. pp. 37–56. Available from: http://dx.doi.org/10.5772/56707.

GROVES, D.G., FISCHBACH, J.R., KALRA, N., MOLINA-PEREZ, E., YATES, D.N., PURKEY, D.R., FENCL, A., MEHTA, V., WRIGHT, B., and PYKE, G., 2014. *Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework.* Denver, USA. Available from: http://www.waterrf.org/Pages/Projects.aspx?PID=4262.

HAASNOOT, M., KWAKKEL, J.H., WALKER, W.E., and TER MAAT, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*. 23 (2), pp. 485–498. Available from: http://dx.doi.org/10.1016/j.gloenvcha.2012.12.006.

HARRIS, I., JONES, P.D., OSBORN, T.J., and LISTER, D.H., 2014. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology.* 34, pp. 623–642. Available from: https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.00/ge/.

JACK, C. and JONES, R., 2019. *Climate Risk Narratives: 'Humble' Science.* Cape Town, South Africa. Available from: http://www.fractal.org.za/wp-content/uploads/2020/03/IS4-Climate-risk-narratives-humble-science.pdf.

JICA, 1995. *The study on the National Water Resources Master Plan in the Republic of Zambia Final Report Supporting report [D] Hydrogeology.* Lusaka, Zambia: Japan International Coorperation Agency.

JICA, 2008. Chapter 4 Existing condition of Lusaka city. In: *Summary on the Preliminary Study of the Master Plan Study for Establishing Lusaka South Multi-Facility Economic Zone in Republic of Zambia.* Lusaka, Zambia: Japan International Coorperation Agency.

JICA, 2009. *The study on comprehensive urban development pln for the city of Lusaka in the Republic of Zambia.* Lusaka, Zambia: Japan International Coorperation Agency.

JOHANNESSEN, Å. and WAMSLER, C., 2017. What does resilience mean for urban water services? *Ecology and Society*. 22 (1). Available from: https://www.ecologyandsociety.org/vol22/iss1/art1/.

JONES, L., CARABINE, E., HICKMAN, A., LANGSTON, L., MOOSA, S., and MUKANYA, R., 2014. *Exploring the role of climate science in supporting long-term adaptation and decision-making in sub-Saharan Africa.* London, UK:CDKN.

KAVONIC, J., MCCLURE, A., ZIERVOGEL, G., VOGEL, C., and BOUWER, R., 2017. *Building city-region resilience in Africa : lessons from practice*. Cape Town, South Africa.

KEMP, L., FAIRHURST, L., and TARRYN, P.R., 2011. *Sub-Saharan African Cities : A five-City Network to Pioneer Climate Adaptation through Participatory Research & Local Action Maputo Baseline Study* February 2011 Authors : Quayle Edited by : Lucinda Fairhurst. Cape Town, South Africa.

KLING, H. and PREISHUBER, M., 2013. *Zambezi Decision Support System – User ' s Manual.* Vienna, Austria.

KLING, H., STANZEL, P., and PREISHUBER, M., 2014. Impact modelling of water resources development and climate scenarios on Zambezi River discharge. *Journal of Hydrology: Regional Studies.* 1, pp. 17–43. Available from: http://ac.els-cdn.com/S2214581814000032/1-s2.0-S2214581814000032-main.pdf?_tid=631eb380-4125-11e7-9082-00000aab0f01&acdnat=1495701629_c211904461398483af3a5778460e1e7f [Accessed 25 May 2017].

KWAKKEL, J.H., HAASNOOT, M., and WALKER, W.E., 2016. Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for model-based decision support under deep uncertainty. *Environmental Modelling and Software.* 86, pp. 168–183. Available from: http://dx.doi.org/10.1016/j.envsoft.2016.09.017.

LUDWIG, F., VAN SLOBBE, E., and COFINO, W., 2014. Climate change adaptation and Integrated Water Resource Management in the water sector. *Journal of Hydrology.* 518 (PB), pp. 235–242. Available from: http://dx.doi.org/10.1016/j.jhydrol.2013.08.010.

PEGASYS AND WWF, 2016. *Exploring shared risks and opportunities in the Kafue Flats*. Lusaka, Zambia: WWF. Available from: http://d2ouvy59p0dg6k.cloudfront.net/downloads/water_in_the_zambian_economy_final_2nd_edition.pdf.

POFF, N.L., BROWN, C.M., GRANTHAM, T.E., MATTHEWS, J.H., PALMER, M. a., SPENCE, C.M., WILBY, R.L., HAASNOOT, M., MENDOZA, G.F., DOMINIQUE, K.C., and BAEZA, A., 2015. Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Climate Change.* (September), pp. 1–23. Available from: http://www.nature.com/doifinder/10.1038/nclimate2765.

POLK, M., 2015. Transdisciplinary co-production: Designing and testing a transdisciplinary research framework for societal problem solving. *Futures.* 65, pp. 110–122. Available from: https://ac.els-cdn.com/S0016328714001864/1-s2.0-S0016328714001864-main.pdf?_tid=f2a30546-c52e-11e7-87b9-00000aacb362&acdnat=1510219289_fd0d7323f333fb30a2df8334c69331f1 [Accessed 9 November 2017].

PURSHOUSE, H., ROXBURGH, N., JAVORSZKY, M., SLEIGH, A., and EVANS, B., 2015. *Modelling formal and informal domestic water consumption in Nairobi.*

RASUL, G. and SHARMA, B., 2015. The nexus approach to water-energy-food security: an option for adaptation to climate change. *Climate Policy.* 16 (January). Available from: http://link.springer.com/10.1007/978-3-642-40455-9 [Accessed 15 March 2018].

RAY, P.A. and BROWN, C.M., 2015. *Confronting Climate uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework.* Washington DC,USA: World Bank.

SPALDING-FECHER, R., CHAPMAN, A., YAMBA, F., WALIMWIPI, H., KLING, H., TEMBO, B., NYAMBE, I., and CUAMBA, B., 2016. The vulnerability of hydropower production in the Zambezi River Basin to the impacts of climate change and irrigation development. *Mitigation and Adaptation Strategies for Global Change*. 21 (5), pp. 721–742.

SPALDING-FETCHER, R., YAMBA, F., WALIMWIPI, H., KLING, H., TEMBO, B., NYAMBE, I., CHAPMAN, A., and CUAMBA, B., 2014. Water Supply and Demand Scenarios for the Zambezi River Basin. *Climate Change and Upstream Development Impacts on New Hydropower Projects in the Zambezi Project.* (January), pp. 1–68.

STEINSCHNEIDER, S., MEARNS, L.O., and BROWN, C., 2015. Expanded Decision-Scaling Framework to Select Robust Long-Term Water-System Plans under Hydroclimatic Uncertainties Expanded Decision-Scaling Framework to Select Robust Long-Term Water-System Plans under Hydroclimatic Uncertainties. *Journal of Water Resources Planning and Management.* (April), pp. 04015023-1-04015023–1.

STEYNOR, A., PADGHAM, J., JACK, C., HEWITSON, B., and LENNARD, C., 2016. Co-exploratory climate risk workshops: Experiences from urban Africa. *Climate Risk Management*. 13, pp. 95–102. Available from: https://ac.els-cdn.com/

S221209631630002X/1-s2.0-S221209631630002X-main.pdf?_tid=9046c82c-c52b-11e7-8def-00000aab0f26&acdnat=1510217835_86bd8cbef80ed47ab0e39103fa308a2b [Accessed 9 November 2017].

TAYLOR, R., BUTTERFIELD, R., BHARWANI, S., TAYLOR, A., and DEVISSCHER, T., 2017. *Research Methods for Understanding and Supporting Decision Processes in African Cities.* Oxford, United Kingdom. Available from: http://www.fractal.org.za/wp-content/uploads/2017/07/Research-methods-for-decision.pdf.

THE WORLD BANK, 2010. *The Zambezi River Basin: A Multi-Sector Investment Opportunities Analysis.* World Bank. Washington DC, USA. Available from: papers3://publication/uuid/4F29E4F1-5CC3-4F62-B16A-2907C3363C1A.

UHLENDAHL, T., SALIAN, P., CASAROTTO, C., and DOETSCH, J., 2011. Good water governance and IWRM in Zambia: Challenges and chances. *Water Policy.* 13 (6), pp. 845–862. Available from: https://www.ircwash.org/sites/default/files/Uhlendahl-2011-Good.pdf [Accessed 23 February 2018].

UN-WATER, 2018a. *Water, Food and Energy* [online]. [online]. Available from: http://www.unwater.org/water-facts/water-food-and-energy/ [Accessed 13 March 2018].

UN-WATER, 2018b. *Climate Change* [online]. [online]. Available from: http://www.unwater.org/water-facts/climate-change/ [Accessed 13 March 2018].

UNESCO, 2012. *Managing Water under Uncertainty and Risk.* UN Water Reports. Geneva, Switzerland. Available from: http://unesdoc.unesco.org/images/0021/002156/215644e.pdf.

UNU-INWEH, 2013. Water Security & the Global Water Agenda. The UN-Water analytical brief. *Journal of Chemical Information and Modeling.* Ontario, Canada. Available from: http://www.unwater.org/publications/water-security-global-water-agenda/.

WALKER, N.J., IIPINGE, K.N., CULLIS, J.D.S., SCOTT, D., MFUNE, J., WOLSKI, P., and JACK, C., 2018. Integrating climate change information into long term planning and design for critical water related infrastructure in Windhoek and other African cities. *Water - Special issue: Transdisciplinarity and Knowledge Co-production: Reflections from Water Governance.* 10 (10), pp. 1366–1378. Available from: http://www.futureclimateafrica.org/wp-content/uploads/2018/07/walker-et-al-2017-integrating-climate-change-information-into-long-term-planning-and-design-for-critical-water-related-infrastructure-in-windhoek-and-other-african-cities.pdf.

WALTINA SCHEUMANN, n.d. *Coordinating Planning in the Agricultural and Water Sectors: Zambia*. Available from: https://www.die-gdi.de/uploads/media/Two-Pager_5.2016.pdf [Accessed 23 February 2018].

WILLYARD, C., SCUDELLARI, M., and NORDLING, L., 2018. How three research groups are tearing down the ivory tower. *Nature* [online]. Available from: https://www.nature.com/articles/d41586-018-06858-4.

WWF, 2017. *Kafue Flats Status Report: Monitoring the Pulse of the Blue Heart of Zambia's Economy*. Lusaka, Zambia: WWF.