Climate Change

Urban Water Supply Solutions

Lessons Learned

# Sustaining Urban Water Supply under Climate Change

**Lessons from selected rapidly growing cities in Southern Africa and China**

UN-HABITAT

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# Contents

# Foreword

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Water is the basis for life, and meeting water supply demand is a global challenge, particularly in developing countries. In 2020, it was estimated that two billion people lived in water-stressed regions with no access to a safely managed drinking water service on premises, available when needed and free of contamination. This condition is expected to worsen in some regions due to climate change and rapid population growth. The United Nations World Water Development Report 2020 estimates that by 2050, some 685 million people will live in over 570 cities; and will likely face a decline in freshwater availability of at least ten per cent because of climate change. Water use worldwide has been growing at more than twice the rate of the global population in the last century. Combined with a more erratic and uncertain supply, this will aggravate the situation of water-stressed regions and generate water stress in areas with currently abundant water resources.

The 2030 Agenda for Sustainable Development, adopted in September 2015 by world leaders at the United Nations General Assembly, includes Sustainable Development Goal (SDG) 6 to "Ensure availability and sustainable management of water and sanitation for all". Specifically, the Goal commits to the following targets:

Target 6.1 - "Achieve universal and equitable access to safe and affordable drinking water for all".

Target 6.3 - "Improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally".

Target 6.4 - "Substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity".

Target 6.5 - "Implement integrated water resources management at all levels, including through transboundary cooperation as appropriate".

Target 6.6 - "Protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes".

Target 6.a - "Expand international cooperation and capacity-building support to developing countries in water-and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies".

Agenda 2030 includes Goal 11 to "Make cities and human settlements inclusive, safe, resilient and sustainable". This Goal commits countries to "ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums" (target11.1). Additionally, Goal 13 requires governments to "Take urgent action to combat climate change and its impacts", specifically to "integrate climate change measures into national policies, strategies and planning" (target 13.2); to "improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning" (target 13.3).

In the New Urban Agenda, adopted in 2016 at the third United Nations Conference on Housing and Sustainable Urban Development (Habitat III) in Quito, Ecuador, Member States committed to long-term urban and territorial planning processes and spatial development practices that incorporate integrated water resources planning and management, considering the urban-rural continuum on the local and territorial scales and including the participation of relevant stakeholders and communities. Agenda 2030 and the New Urban Agenda reaffirm the promise of world leaders to seek solutions to sustainable water supply and management. Increasing water-use efficiency while advocating for sustainable water supply practices, recycling and reuse are urgent global priorities.

Alternative water sources such as wastewater, stormwater run-off and desalination plants, and instituting measures like water harvesting and rationing, can help relieve water stress. Safe wastewater treatment, reuse and recycling is, so far, an untapped and significant resource. Developing countries can learn from China's experience in wastewater treatment technology, including removal of hazardous chemicals for safe use. The cities of Windhoek (Namibia) and Shanghai (China) case studies suggest that future innovative solutions will require a mix of the following: cost-effective water treatment technologies, wastewater reuse, sea and groundwater desalination, water harvesting (rainwater, stormwater, aquifer recharge) and transboundary water sources. The cities of Bulawayo (Zimbabwe), Gaborone (Botswana) and Windhoek also propose tapping into transboundary river sources. Promoting water-use efficiency in Shanghai through technologies used in industry and household appliances plays a central role in meeting water supply demand. Furthermore, strict urban planning standards coordinated with long-term engineering and water supply plans and strategies ensure adequate water supplies to all new developments in China.

This publication aims to provide a valuable reference source for all those involved in water supply and management in urban areas of developing countries. It aspires to encourage regions, countries and cities to prioritize investment in and the financing of sustainable long-term water supply management actions within the context of climate change in the rapidly urbanizing world.

UN-Habitat and Tongji University are pleased to issue this joint publication. Both institutions remain available to work hand in hand with countries, especially developing ones, towards addressing diverse challenges associated with the increasingly damaging impacts of climate change on cities' capacities to meet their water supply needs.

CHAPTER 1

# Climate Change Dynamics in African Urban Settings

## 1.1 INTRODUCTION

Climate change and urban development dynamics in Africa: rationale for the publication

The resilience of African cities is constantly under threat from an assortment of forces, one of which is global climate change. While climate change or variability is mainly thought of as a problem in agriculture under rural set-ups, actually, its impact in urban areas, where most Africans will live by 2030, is equally devastating (Emilsson and Sang, 2017; Miller and Hutchins, 2017).

Cities are sustained by food and water supplies, which are subject to climatic forces. Africa is urbanizing much faster than the other continents, putting infrastructure and service delivery systems under immense pressure (Parnell and Walawege, 2011; Anderson *et al*., 2013). This situation is compounded by climate change and variability. The pace of housing delivery is slower than the rate of urbanization, resulting in slums whose residents are exposed to climate change or variability, natural hazards and poor service delivery (Parnell and Walawege, 2011).

UN-Habitat (2003) defines a slum household as a group of individuals living under the same roof and lacking one or more of the following conditions: access to safe water, improved sanitation, sufficient living space, housing durability, and security of tenure. The underprivileged often settle on marginal urban land, typically areas that are considered undesirable and are thus affordable. Exposure to risk is further worsened by overcrowded living conditions, lack of adequate infrastructure and services, unsafe housing, inadequate nutrition, and poor health (Boadi *et al*., 2005). Such conditions increase vulnerability to natural hazards including impacts of climate change, as well as to malnutrition, disease and disability or the loss of basic services, homes, livelihoods and life (Baker, 2012).

Slum development is an indication of urban poverty, which affects the ability of residents to pay for municipal services, such as water supply, sanitation, roads and stormwater drainage (Kulabako *et al*., 2010). Most slum dwellers do not contribute financially to the running of the city but still require its services. The haphazard settlement patterns in slums and inadequate waste management lead to pollution of ground and surface water (Love *et al*., 2005; Mbonambi, 2016; Phiri, 2016). Illegal settlements on sensitive urban ecosystems such as wetlands are common in Africa (Beuel *et al*., 2016). Urban development regulations and standards are often ignored in slums in favour of political expediency (Fox, 2014). Urban physical planning and engineering standards should therefore aim to provide climate-resilient water supply and stormwater infrastructure and to manage urban sprawl. According to Monzon (2015), Tsolakis and Anthopoulos (2015), the urban economy needs to be managed holistically to enhance efficiency and sustainability within the city system.

Several studies have examined the impacts of climate change on water supply in coastal cities and humid regions (Nyong and Niang-Diop, 2006; Hunt and Watkiss, 2011; Balaban, 2012; Ziervogel and Parnell, 2014; Leal Filho *et al*., 2019). These studies have also looked at disastrous impacts of flooding and mudslides. Few studies have focused on inland cities within semi-arid regions, where the available water resources are limited and highly variable over the years (Lal, 2004; Herrera-Pantoja and Hiscock, 2015; Morote *et al*., 2019). This publication presents empirical evidence on the impacts of climate change and rapid urbanization on water supply in four selected inland cities within the semi-arid region of Southern Africa: Bulawayo, Zimbabwe; Gaborone, Botswana; Lusaka, Zambia; and Windhoek, Namibia. It further compares this with a case study of Shanghai in China. The publication reviews the effectiveness of practical responses and solutions that are helping or could help these cities avert an imminent crisis of water supply.

For an in-depth exploration of resilience dimensions, the African cities selected are in the same regional block (identical regional policy context), within close geographic proximity, and with similar socio-economic characteristics. They are either cities already doing something about their water supply predicament, or are considering actions to be taken. The cities, to varying degrees, are not as well-known, well-researched or publicized. Yet they present unique and captivating stories of how they have managed urbanization and water supply. Shanghai has promising advanced technologies for addressing water supply challenges and was brought in for comparison and positive lessons.

This publication is not based on primary data but is aimed at providing value to a variety of concerned stakeholders. The report is intended to help city councils, residents and water utilities learn from each other the strategies or approaches being used to tackle shared problems, thus facilitating the dissemination of best practices. The report will also help central governments better appreciate real challenges faced by their cities and see how best to support the councils and utilities to tackle them. At a regional level, organizations such as the Southern Africa Development Community (SADC), the Global Water Partnership (GWP) and river basin organizations will be appraised of sub-regional urban water supply issues, which will contribute to better planning their interventions with such cities. The publication will also inform academia on emerging research areas.

## 1.2. WATER RESOURCES MANAGEMENT AND CLIMATE CHANGE ARCHITECTURE IN SADC AND SELECTED CITIES

SADC is interesting to study because of its high level of regional integration through the community's Protocol on Shared Watercourses and the regional water development blueprints based on Regional Strategic Action Programmes (SADC www.sadc.int). The SADC Water Division has developed a climate change strategy and promoted the Integrated Water Resources Management (IWRM) approach in close collaboration with the Global Water Partnership and other cooperating entities. SADC also has a vibrant network of river basin organizations whose members would benefit from lessons presented in this book. Other key regional players in water and climate change in the SADC region include the Climate Resilient Infrastructure Development Facility, the Food, Agriculture and Natural Resources Policy Analysis Network (or FANRPAN), WaterNet and the SADC Groundwater Management Initiative.

The selected African cities in the SADC region are shown in figure 1.1.

Figure 1.1: Map of the SADC region showing the selected four case study cities

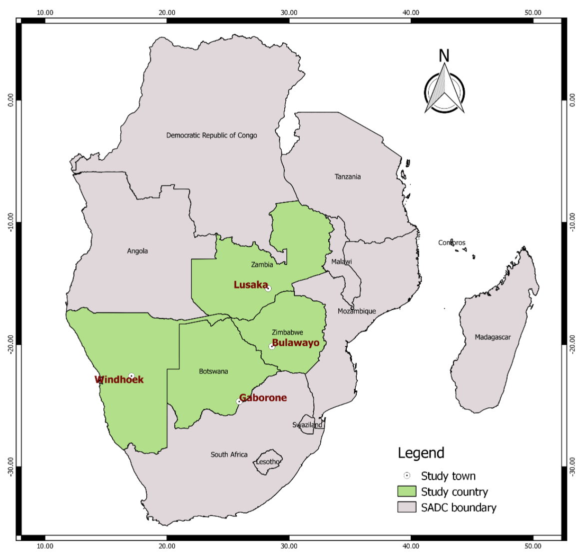
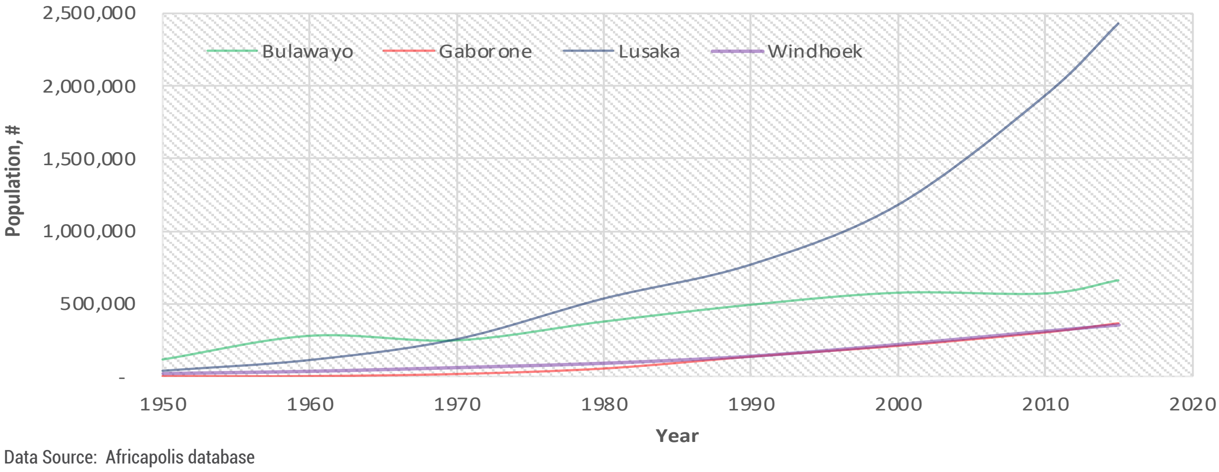


Figure 1.2: Population size and growth patterns of four study cities in Southern Africa since 1950




Data Source: Africapolis database

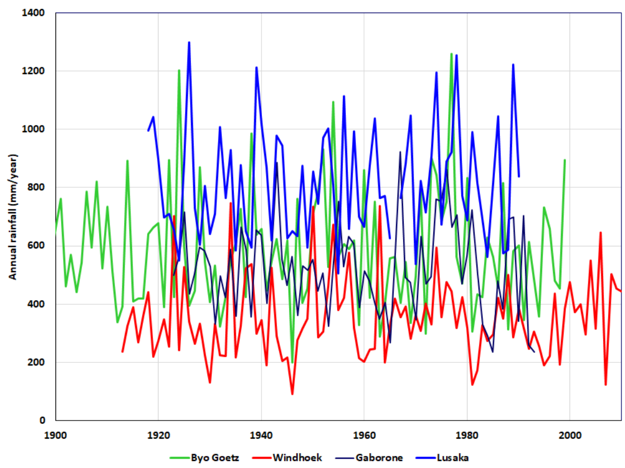
Figure 1.2 gives the relative population sizes of the selected cities and their growth trends. It also shows that Bulawayo, Gaborone and Windhoek have similar rapid urban growth patterns. They are also in semi-arid areas with limited surface and groundwater resources. Windhoek receives an average rainfall of 372 mm/year, while this is 585 mm/year for Bulawayo and 600 mm/year for Gaborone. Lusaka receives about 850 mm/year of rainfall. Gaborone has successfully managed to eradicate informal settlements, while Lusaka and Windhoek are struggling (62 per cent and 30 per cent respectively live in informal settlements) ). Bulawayo has a different pattern of informal settlements. These were developed illegally but in accordance with modern town planning standards. However, essential municipal services were not installed before plots were parcelled out by private land developers.

Although Lusaka has a strong regulatory system, service coverage remains low, leading to most residents in formal areas obtaining water from their own boreholes and shallow wells. With a higher portion of the population living in informal settlements, a large area is served by non-governmental organizations (NGOs) or through informal water supply systems, with, residents mobilized into informal water supply initiatives. Unlike the other cities, Lusaka has substantial groundwater resources and is close to the Kafue River, which is perennial.
In terms of water supply sources, the four cities use surface, groundwater, wastewater recycling and rainwater harvesting.

Unlike the selected African cities, Shanghai is a much larger metropolis of nearly 25 million people and has modernized rapidly over the past 30 or so years. It has witnessed a change from warm temperate summer months to very hot temperatures, but its good city planning and resilience systems have ensured security of water supplies under a changing environment. Shanghai's expansion and development has been underpinned by a green cities development philosophy (Zhang, 2013) and it can provide important lessons for African cities.

The rainfall pattern in the selected African cities from 1900 to 2020, shown in figure 1.3, demonstrates a high inter-annual variability, which ultimately affects available water resources. In addition, there is evidence of multi-decadal variability, with several years experiencing generally low and high rainfall followed by several years with high and low rainfall.

Figure 1.3: Rainfall patterns for selected African cities 1900–2020



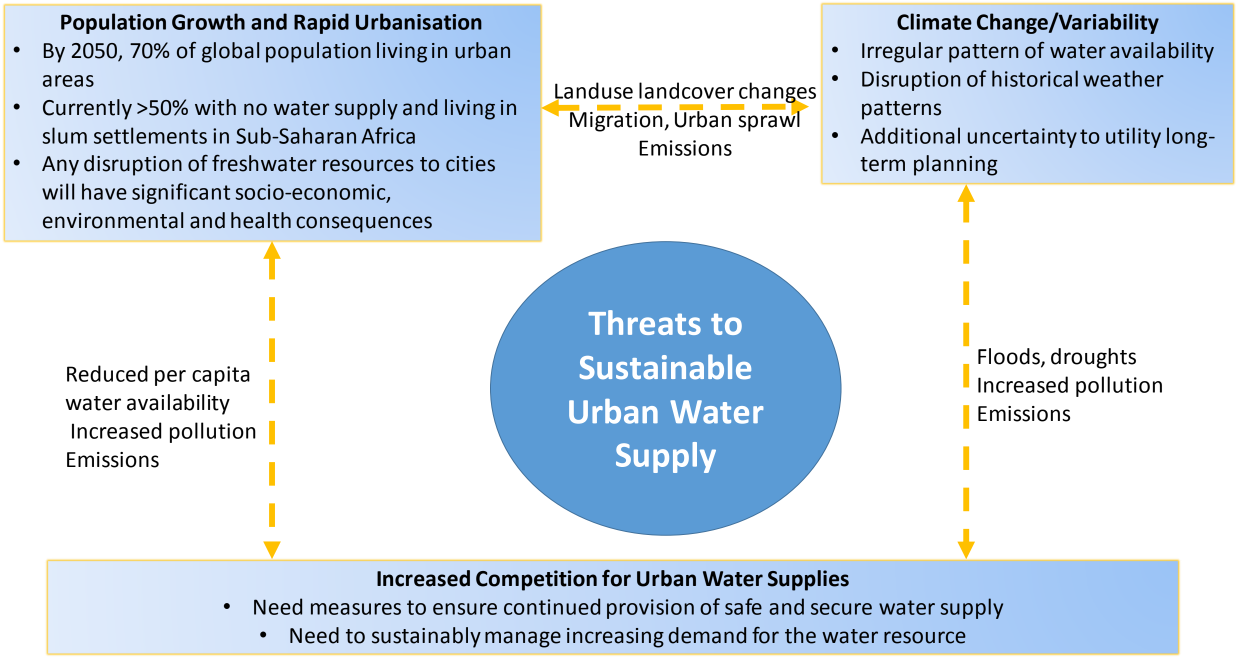
## 1.3 URBAN WATER SUPPLY, URBANIZATION AND CLIMATE CHANGE/VARIABILITY NEXUS

The impact of climate change and variability in arid and semi-arid, rapidly growing cities is an area that is not fully understood but increasingly getting attention as a factor in building urban resilience (Moench *et al*., 2011; Meerow *et al*., 2016). Figure 1.4 shows the connection between urban water supply, urbanization and climate change and variability. As described by Kundzewicz (2008), climate change is altering the hydrological cycle and thus changing the timing and intensity of rainfall and directly affecting the quantity and quality of water resources for different uses. This change in the hydrological cycle can affect a water utility's capacity to sustain water service provision and the economic viability and cost-effectiveness of water treatment and distribution. Utilities need, therefore, to build resilience to extreme weather events as an integral part of water supply management (Velasco *et al*., 2018).

The impacts of drought on water supply include low flows and reduced water levels, which can increase the concentration of pollutants and nutrients in waterbodies (Mosley, 2015). High temperatures can create conditions for increased waterborne pathogens in the water supply system (Furth, 2010). Higher temperatures can increase cyanobacterial blooms, increasing the risk of cyanotoxins and natural organic matter in water sources (Merel *et al*., 2013). Reduced groundwater tables and surface water flows lead to reduced supply and, potentially, the use of unsafe water sources (De Wit and Stankiewicz, 2006). Low water availability for washing, cooking and hygiene increases exposure to waterborne contamination.

Floods can lead to damage of infrastructure with subsequent economic, health and environmental impacts (Zeleňáková *et al*., 2017). High levels of rainfall and run-off can increase loading of pollutants, contaminants and sediments in surface waters (Zonta *et al*., 2005). Flooding can also lead to contaminated water entering groundwater through unprotected wells (Zeleňáková *et al*., 2017). Flooding can also cause overflows and contamination from sewerage systems.

Figure 1.4: Urban water supply, urbanization and climate change/variability nexus




## 1.4. BACKGROUND AND CONTEXT

### 1.4.1 Climate change and variability in Africa

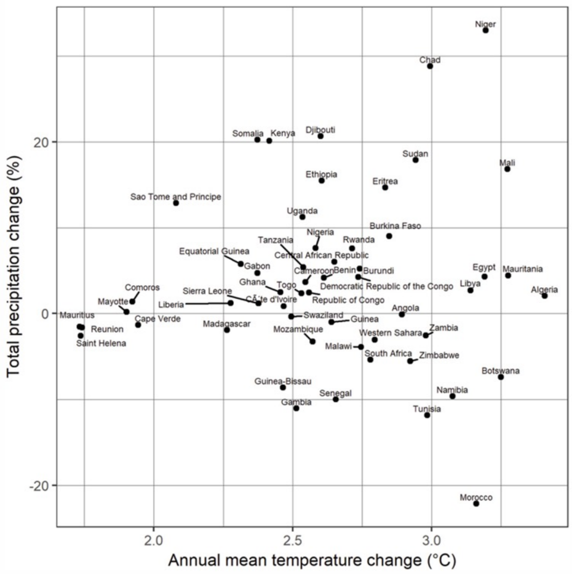
Temperature records show that climate in Southern Africa has been changing (Kusangaya *et al*., 2014). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) asserts that further change in climate is inevitable and this will pose challenges to economic development. Climate change refers to the alteration of long-term average weather conditions (mainly temperature, rainfall, radiation, wind and cloud cover) and without reverting to original state (McMichael *et al*., 2003; IPCC, 2012). The changes are assessed over periods ranging from decades to centuries. In contrast, climate variability refers to the changes in weather conditions within a day or season, and from one year to another. Climate variability results from mechanisms within the climate system that do not change the long-term average conditions (IPCC, 2014).

The prediction of the future state of the climate is done using global and regional climate models that attempt to represent evolution of atmospheric-land-ocean processes determining the climate. These predictions have some uncertainty due to inadequate representation of these processes as a result of the current state of knowledge and limited observational data for some parts of the world, especially over oceans (Aloysius *et al*., 2016).

Historical data show that average temperatures in Southern Africa have risen by 0.5°C over the last century (Blunden *et al*., 2018). Atmospheric temperatures are predicted to increase by 1.5–3.5°C across Africa by 2050, depending on current and future emission rates of greenhouse gases (Ajjur and Al Ghamdi, 2021); see also figure 1.5. According to the Intergovernmental Panel on Climate Change (2014), temperatures in Southern Africa could rise by between 1°C and 3°C by 2080 if no concrete actions are taken to reduce emission rates of greenhouse gases. The November 2021 Conference of Parties (COP26) held in Glasgow, Scotland, agreed to control greenhouse gas emissions to keep temperature rises within 1.5°C, which scientists say is required to prevent a climate catastrophe.

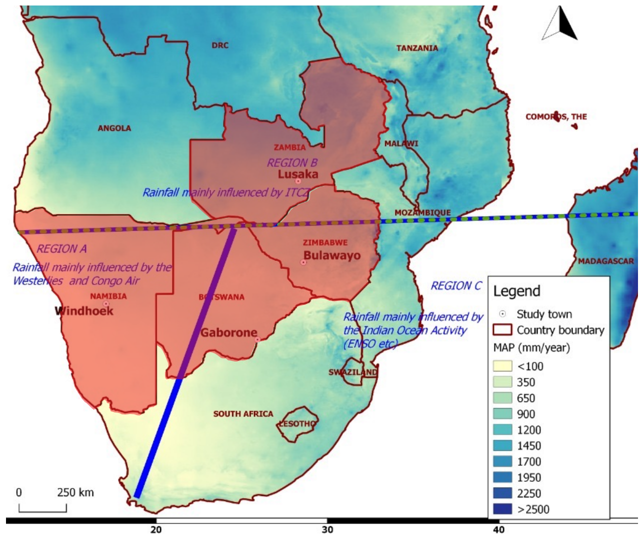
Some regions in Africa are predicted to have increase in rainfall while other regions will experience a decrease (figure 1.5). However, most countries in Southern Africa are predicted to experience a decrease in rainfall by 2050. There is considerable uncertainty regarding the direction and magnitude of the change of rainfall over Africa. The general consensus is that under high (RCP8.5) greenhouse gas emission scenarios, the Southern and Northern African regions are predicted to experience decreases in mean annual rainfall by the mid and late twenty-first century (Miller, 2020; IPCC, 2021. The most notable climate changes predicted in Southern Africa

Figure 1.5: Climate model projections for Africa by 2050, based on multiple CMIP5 models




Source: Girvetz et al. (2018)

Figure 1.6: Three rainfall determining systems in Southern Africa and resulting distribution across the region




Source: Adapted from Lesolle (2012)

are a decrease in rainfall estimated at 10–20 per cent, potential evaporation increasing by 10–25 per cent, and run-off decreasing by 26–40 per cent) (IPCC, 2014; Maúre *et al.*, 2018).

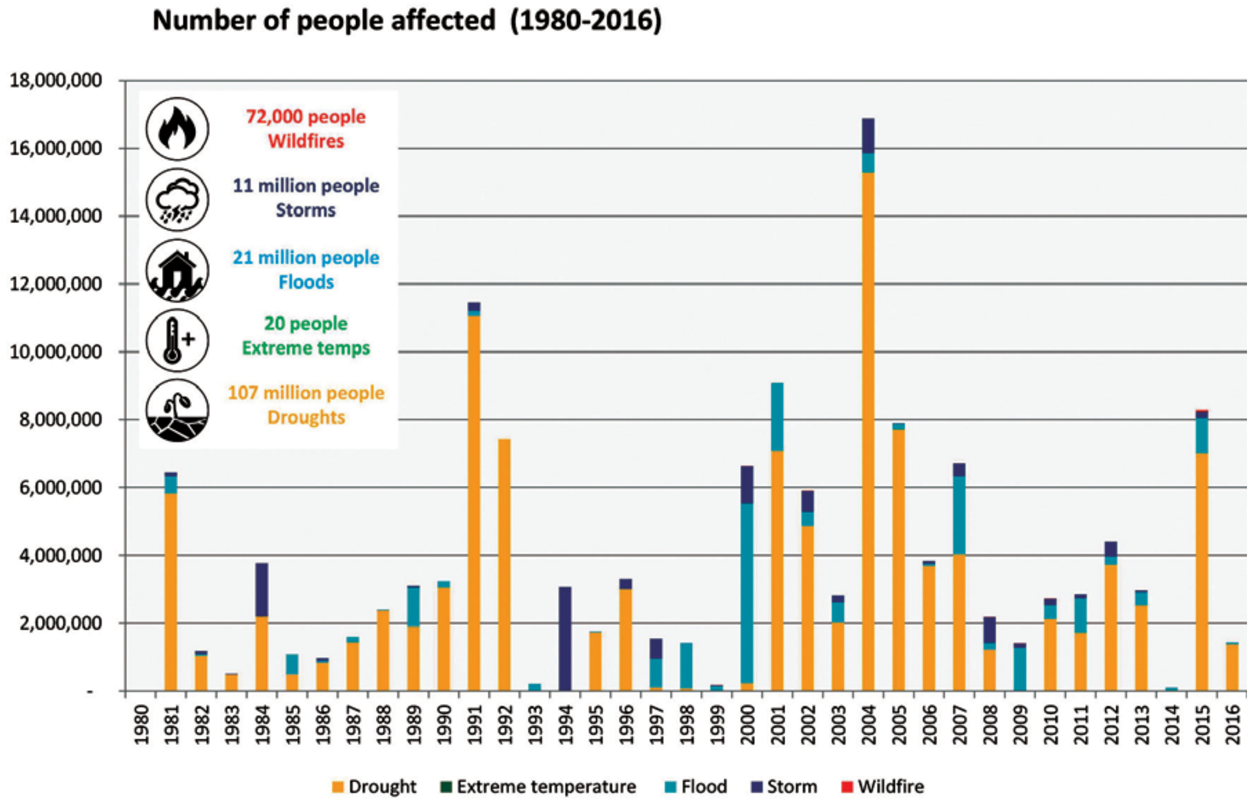
### 1.4.2 Climate challenges in Southern Africa

Rainfall in Southern Africa is influenced by inflow of moisture brought by the south-east trade winds from the Indian Ocean, north-westerly winds, and westerly winds — the Congo Air Mass (see figure 1.6). The annual north-south migration of the Intertropical Convergence Zone affects rainfall in Southern Africa (Lesolle, 2012). During an El Niño year, Southern Africa tends to experience below average rainfall, while East Africa receives above average rainfall (Byakatonda *et al.*, 2020). Sea surface temperatures over the Indian Ocean also affects rainfall in Southern Africa.

Data from 1950 onwards suggest that climate change and variability have altered the magnitude and frequency of some extreme weather events in Southern Africa (IPCC, 2014; Kusangaya *et al.*, 2021). There has been an increase in the frequency and intensity of El Niño episodes, particularly 1982–1983; 1991–1992; 1994–1995; and 1997–1998; 2002–2003; 2004–2005; 2006–2007; 2009–2010; 2014–2016; and 2018–19 (Donegan, 2019; United States Climate Prediction Center, 2019). Nhamo and Chikodzi also documented the impacts of flooding and cyclones in Southern Africa. Some of these cyclones include Danae (in 1976), Emilie (in 1977), Berobia (in 1986), Lissette, (in 1997), Eline (in 2000), Japhet (in 2003), Dineo (in 2017), Idai (in 2019), Kenneth (in 2019) and Eloise (in 2021). A number of cyclones were also recorded in 2022. A study by Kativhu *et al.* (2021) typically shows how such episodes negatively affect water, sanitation and hygiene services in urban areas.

The impacts of climate change and variability in Southern Africa are described by Davis-Reddy and Vincent (2017) and summarized in figure 1.7. The modifications in rainfall are best expressed as changes in intensity, extreme rainfall events (storms and cyclones) and changes in the rainfall season (onset, cessation and length) (Dunning *et al.*, 2018; Maúre *et al.*, 2018). Also predicted are significant changes in the seasonal pattern of rainfall, including delayed, unpredictable onsets and shorter and more intense rainfall events, implying an increasing frequency of floods and droughts (Beilfuss 2012; SARDC, 2015; Maúre *et al.*, 2018). Lafferty (2009) and Kotir (2011) predict that the agricultural seasons could change and planting times could vary for different crops, more pests attracted, and malaria could spread to places where it is not endemic. Studies by Teixeira *et al.* (2013) show that high temperatures could result in heat stress and changes in natural ecosystems. According to Cosgrove and Loucks (2015), there would therefore be challenges for agriculture, water supply, health and other key socioeconomic sectors if practices do not adapt to these changes.

Figure 1.7: Number of people affected by each major category of climate in Southern Africa since 1980



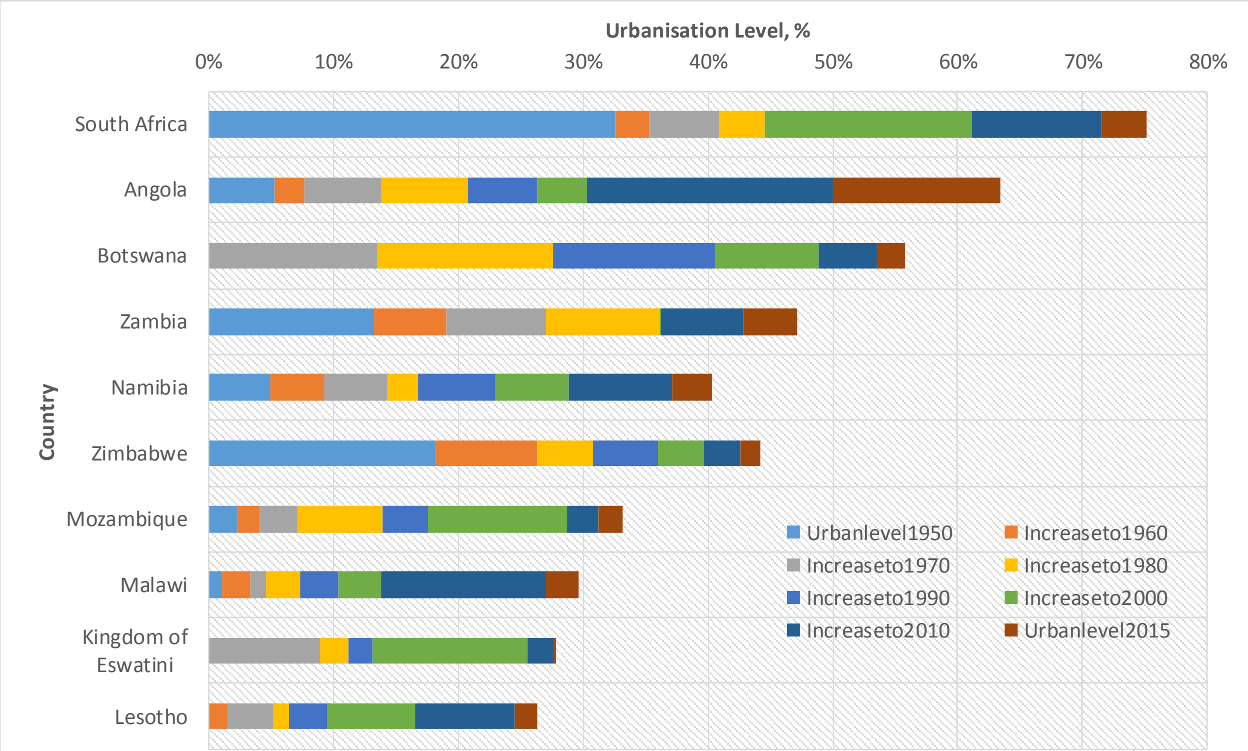

Source: Davis-Reddy and Vincent (2017)

### 1.4.3 Rapid urbanization challenges

Africa is regarded to be the fastest urbanizing continent; in the last 25 years urban population has more than doubled almost all across sub-Saharan Africa (Yiran *et al.*, 2020). More than 472 million people currently stay in urban areas and this number is projected to double over the next 25 years (Saghir and Santoro, 2018). Africa's share of global urban dwellers is projected to increase from 11.3 per cent in 2010 to 20.2 per cent by 2050 (Awumbila, 2017). Urban centres may play a critical role in fighting poverty and sustaining economic growth, and are thus often considered the future of prosperity in the developing world (UNEP, 2011).

Southern African countries are rapidly urbanizing at rates ranging 1–13 per cent (see figure 1.8). Some scholars, such as Hope (2009) and Winsemius *et al*. (2018), attribute these high growth rates to push factors from rural areas, such as poverty, land tenure and shortages, poor agricultural returns and climatic disasters like floods and droughts. Others like Race (2010) identify pull factors that attract people to the cities, such as available and perceived better services in education, health facilities, employment opportunities and the 'bright lights'. Whether urbanization is due to push or pull factors, it is true to say that in most cases urban population growth has outpaced the expansion of local economies, formal employment opportunities, housing and infrastructure provision (Güneralp *et al*., 2020). This has led to slums in peri-urban areas where opportunities are mainly for self-employment in the flourishing informal sector. Other attendant challenges of rapid urbanization are inadequate waste disposal, limited access to potable water and sanitation, high levels of air and water pollution, unemployment and homelessness (Boadi *et al*., 2005; Olalekan, 2014). Consequently, urban local authorities operate in crisis mode in which long-term planning is invariably sacrificed in favour of quick-fix solutions to meet the immediate expectations of residents. The literature shows that a combination of climate change and variability as well as rapid urbanization will adversely affect the environment and livelihoods through deforestation, loss of natural habitats, changes and losses in biodiversity, water and air pollution and depletion of water resources (Elmqvist *et al*., 2015; Weiskopf *et al*., 2020; Shukla *et al*., 2021).

Figure 1.8: Urban population growth trends in Southern Africa, 1950–2015




Data Source: The Conversation. Available at https://theconversation.com/climate-change-migration-and-urbanization-patterns-in-sub-saharan-africa-149036

### 1.4.4 Slums or informal settlements

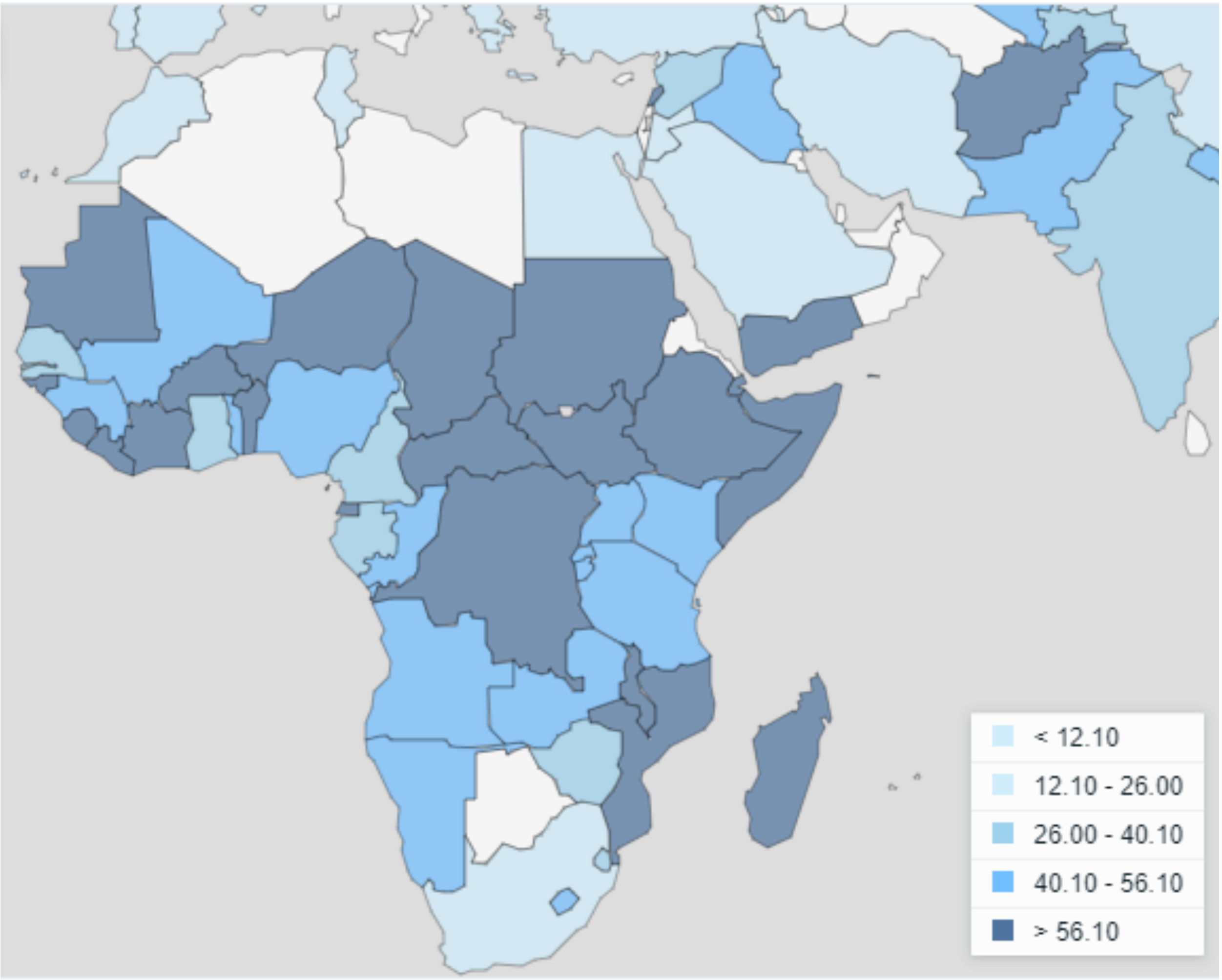
The development of informal settlements, slums and poor residential neighbourhoods is a global phenomenon associated with urbanization (Avis, 2016). An estimated 29 per cent of the world's urban population lives in informal settlements, with an increase of more than 220 million such residents added globally since 1990 (UN-Habitat, 2015; Zhongming *et al*., 2020). Africa south of the Sahara is the world's least urbanized region at 41 per cent but is, paradoxically, also the region with the largest proportion of urban slum dwellers at 54 per cent (Alaazi and Aganah, 2020); see also figures 1.9 and 1.10. Interestingly, Botswana seems to be the only sub-Saharan African country that has successfully managed to deal with slums.

The proportion of urban dwellers using safely managed drinking water services in the region has, as shown in figure 1.10, been increasing steadily. At the same time, the proportion of urban dwellers living in slums has been decreasing.

Informal settlements are normally synonymous with slums, and are identified by the informal status of land tenure, housing structure and services (Sinharoy *et al*., 2019). Inhabitants of informal settlements often have no security of tenure for land or dwellings they inhabit, and they may squat or rent informally. In slums, neighbourhoods usually lack basic services and city infrastructure; buildings do not comply with planning and building regulations. Moreover, these neighbourhoods are often in geographically and environmentally risky areas (Patel, 2013; UN-Habitat, 2021).

A number of interrelated factors are behind the emergence of informal settlements in Africa. These include population growth, rural-urban migration; lack of affordable housing, weak governance (particularly in policy, planning and urban management); economic vulnerability and low-paid work; marginalization, and displacement caused by conflict, natural disasters and climate change (UN-Habitat, 2015; Kovacic *et al*., 2019). Slum dwellers may also face harsh environmental challenges due to the low quality of construction

Figure 1.9: Levels of slum development in Africa




Data source: The World Bank. Sub-Saharan Africa. Available at https://data.worldbank.org/region/sub-saharan-africa

materials used in their buildings (Corburn and Sverdlik, 2019). Many slums are also vulnerable to accidental fires because of overcrowding conditions (Zerbo *et al*., 2020).

Governments often do not formally recognize the existence of informal settlements. As a consequence, these settlements continue to be geographically, economically, socially and politically disengaged from the wider urban systems and excluded from urban opportunities and decision-making (Morrison, 2017). Van Gelder (2013) and Satterthwaite *et al.* (2018) describe the attitudes of city authorities to informal settlements as ranging from opposition and eviction, through reluctant tolerance to support for legalization and upgrading. Upgrading informal settlements, through tenure regularization and provision of infrastructure is widely preferable to relocation, thus helping to preserve existing social and economic networks (Avis, 2016).

### 1.4.5 Disaster risk and urban resilience

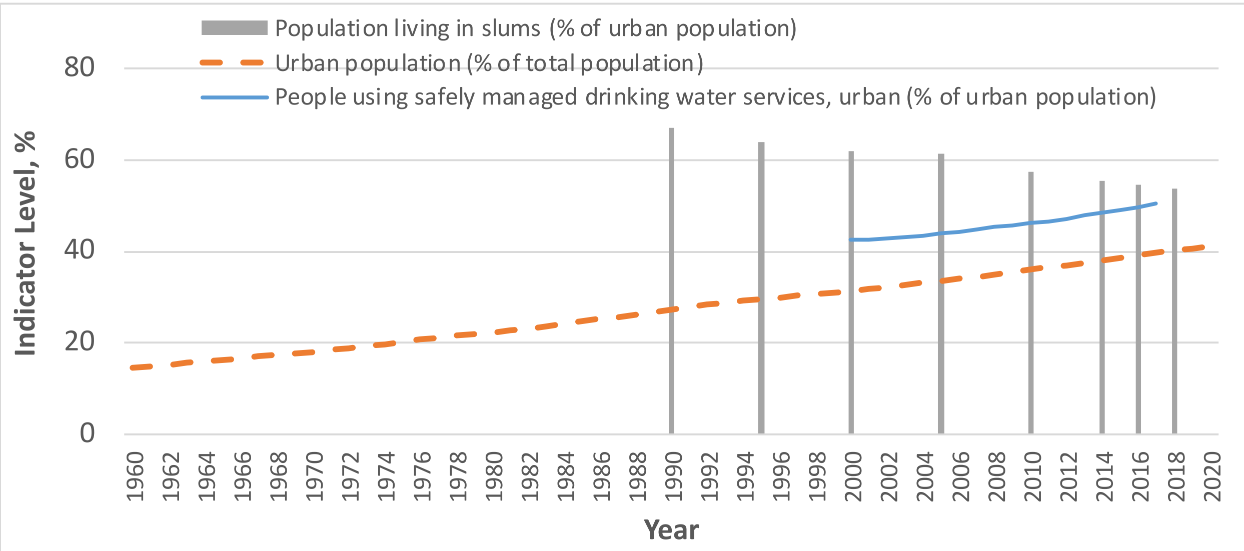
Cities lacking access to adequate infrastructure and basic services, such as safe drinking water, proper sanitation, stormwater drainage and health care are more likely to be adversely affected by natural disasters (Matamanda and Nel, 2021). This may be increasingly pertinent in relation to the projected threats that may arise from, or are exacerbated by climate change and variability. Some cities across the globe may be increasingly exposed to water scarcity and intense flooding due to changes in weather patterns (Hallegatte and Corfee-Morlot, 2011).

The development community generally believes that a well-planned city will be resilient to natural disasters while inadequate urban planning increases vulnerability to these events (Saghir and Santoro, 2018). This is why MacClune and Optiz-Stapleton (2012) argue that climate disasters are more often about development pathways than climate. There is empirical evidence that poorly managed urban growth increases vulnerability to natural disasters (Baker, 2012; Jha *et al*., 2013). Urban planning and development should balance investment in services and infrastructure in the face of rapidly growing demand and threats of exposure to climate hazards. Due to prevailing political and financial constraints, efforts to control the consequences of urbanization are often mismanaged and rarely incorporate urban planning expertise (Matamanda, 2020). Appropriate urban planning principles should be incorporated from the initial design of a project to the regulatory laws so that risks associated with urbanization can be managed (Jha *et al*., 2013).

Adaptive and resilient city governance systems are key drivers for reducing risks. Local governments build resilience by mainstreaming disaster risk reduction into urban planning and management (Malalgoda *et al*., 2010). Climate change adaptation can, therefore, be better employed and sustained over time through integration with existing urban planning and management practices. Cities can be innovative and leverage existing and new resources to meet the shortfalls in service delivery and the adaptation of basic infrastructure.

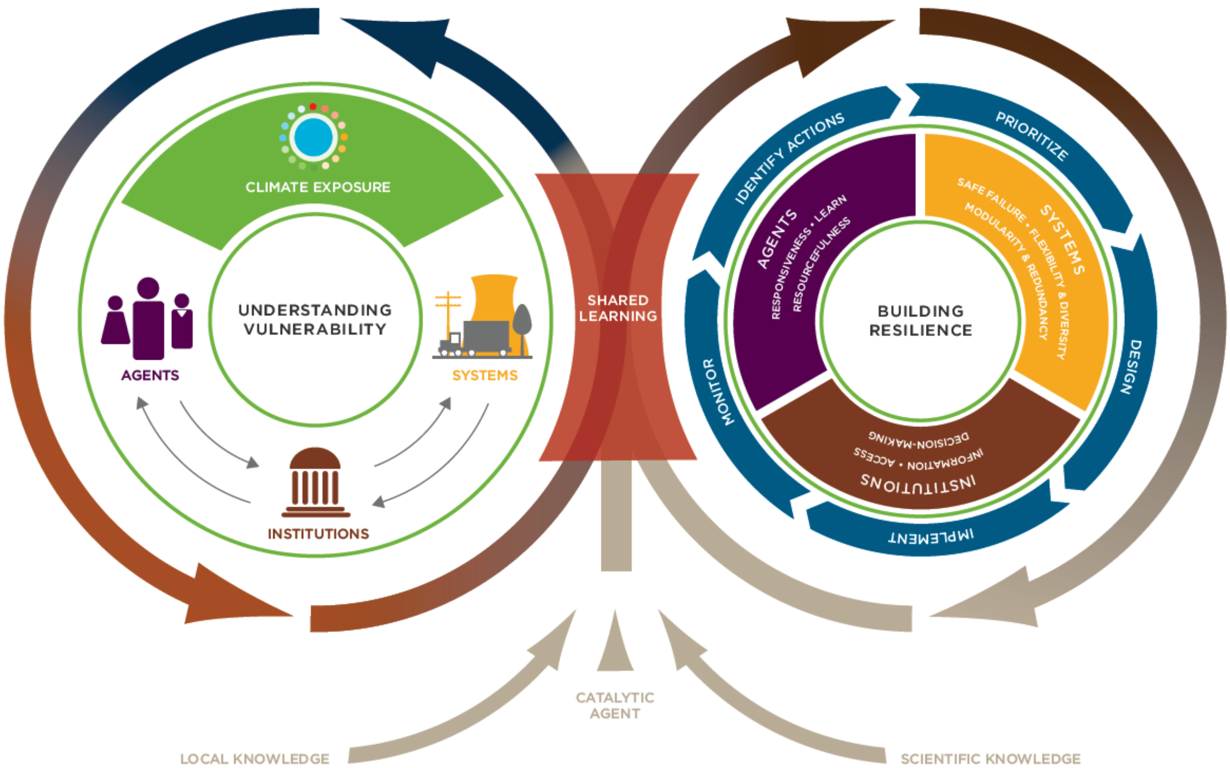
Climate change will have unavoidable impacts on urban systems and populations; hence climate adaptation will be essential (Tyler and Moench, 2012). Adaptation planning can be simplified by operationalizing the concepts of climate vulnerability and resilience (Meerow *et al*., 2016; Davis-Reddy and Vincent, 2017). According to the Asian Development Bank (2014), urban resilience embraces climate change adaptation, mitigation actions and disaster risk reduction while recognizing the

Figure 1.10: Trends in urban population growth, slum dwellers and people using safely managed drinking water services in Africa south of the Sahara, 1960–2020




Data Source: Africapolis. Visualise Urbanisation n Africa. Available at https://africapolis.org/en

Figure 1.11: Graphic representation of Climate Resilience Framework, showing the process of resilience planning




Source: Moench (2014)

complexity of rapid urban growfn and the uncertainty associated with climate change. Adaptation places greater emphasis on considering cities as dynamic systems capable of evolving to survive and thrive in the face of volatile shocks or stresses.

Instead of focusing on discrete measures to adapt to specific perceived future climate risks, it may be more effective for planners to concentrate on building resilience. IPCC (2007) defines resilience as 'the ability of a social or ecological system to absorb disturbances while retaining its basic structure and functions, the capacity of self-organization and the capacity to adapt to stress and change. Resilience requires innovation, flexibility, learning and change to aid recovery from stresses and shocks that may or may not be predictable (Tyler and Moench, 2012). Building resilience has many strategic advantages over conventional system management for complex social-ecological systems that are dynamic and facing high uncertainty (Biggs *et al*., 2015).

Tyler and Moench (2012) describe a framework for urban climate resilience that identifies three generalizable elements of urban resilience: systems (infrastructural and ecological), agents, and institutions as shown in figure 1.11. The framework focuses on the exposure to climate impacts of these three elements and their roles in climate resilience and adaptation. The framework supports planning and strategic policy development using iterative-shared learning techniques. The left side describes a vulnerability diagnostic phase, while the right focuses on the steps to be taken to build resilience. The process involves analysis followed by identification of context-specific actions, prioritization, design, implementation, and monitoring before returning to the basic diagnosis. Factors that are widely cited as contributing to the resilience of systems include flexibility, spatial and functional diversity (ability to perform essential tasks under a wide range of conditions), redundancy and modularity (spare capacity is available for contingency situations), and safe failure (Tyler and Moench, 2012; Yu *et al*., 2020). According to Leichenko (2011), the key urban resilience aspects related to hazard assessment and disaster risk reduction include flexibility and diversity (related to systems) and capacity for learning and innovation. Using water supply as an example, diverse surface and groundwater supplies, a diversified piping network and independently powered pumping units reduce the risk that failures will disrupt service provision. The vulnerability of cities or agents is therefore a function of exposure, fragile systems, constraining institutions, marginalized and low-capacity agents (Moench *et al*., 2011; Moench, 2014).

Unlike systems, agents are capable of deliberation, independent analysis, voluntary interaction and strategic choice in the face of new information. Agents are actors as they introduce volition and intent into choice; they behave in ways that reflect their location and structure within society (that is, as government entities, businesses, community advocates, households and individuals), their preferences, and the opportunities and constraints they perceive (Tyler and Moench, 2012). Agents include individuals (for example, farmers, consumers); households (as units for consumption, social reproduction, education, capital accumulation); and private and public sector organizations (government departments, private firms, civil society organizations). Agents have identifiable but differentiated interests and are able to change behaviour based on strategy, experience and learning. However, while agent behaviour can be changed, this depends on the circumstances and may not be as easy as modifying complex technical infrastructure systems (Duit and Galaz, 2008).

The agent capacities are summarized as (Twigg, 2007):

- **Responsiveness:** Capacity to organize and reorganize in an opportune fashion; ability to identify problems, anticipate, plan and prepare for a disruptive event or organizational failure, and to respond quickly in its aftermath.

- **Resourcefulness:** Capacity to mobilize various assets and resources in order to take action - including the ability to access financial and other assets, including those of other agents and systems through collaboration.

- **Capacity to learn:** Ability to internalize past experiences, avoid repeated failures and innovate to improve performance; as well as to learn new skills.

Institutions condition the way that agents and systems interact to respond to climate stress. The key institutional features that structure the governance environment include: rights and entitlements, decision-making structures, access to information, and processes that support learning and change (Tyler and Moench 2012; Moench, 2014). Institutions of property and tenure, of social inclusion or marginalization and of collective action influence the vulnerability of particular social groups (Adger *et al*., 2005). The pricing structure for urban services is an institution that influences access to infrastructure systems and the resilience they offer, especially for the urban poor (McGranahan, 2002; Baker, 2012). According to Satterthwaite *et al*. (2009) urban planning decisions, such as slum clearance and resettlement, can increase and decrease climate vulnerability, depending on the institution's governing rights, compensation, participatory planning and decision-making associated with the resettlement process. Decision-making processes that build resilience for vulnerable groups are normally participatory and inclusive, allowing those individuals and groups most affected by climate hazards to play an active role in determining how best to avoid them (Morchain and Kelsey, 2016). Communities with access to timely hazard information are better able to respond to climate threats, even in vulnerable sites, especially when this is matched with credible and supportive advice on appropriate response, such as evacuation routes and transport support (Moser and Satterthwaite, 2010; Tyler and Moench, 2012).

Institutional structures that foster learning and change are important tools to build agent capacity. Public and private support for applied research, for publication and presentation of new evidence, and for facilitating critical assessment of new knowledge and its implications all speed the introduction of effective innovation. Marginalization imposes capacity and institutional barriers to adaptation (Tyler and Moench, 2012).

Urban resilience to climate change increases by:

- Strengthening infrastructural and ecological systems to reduce their fragility in the face of climate impacts and to reduce the risk of cascading failures

- Building the capacities of social agents to anticipate and develop adaptive responses, to access and maintain supportive urban systems

- Addressing the institutional factors that constrain effective responses to system fragility or undermine the ability of agents to take action (Muller, 2007; Leichenko, 2011; Cobbinah, 2021; Pamukcu-Albers *et al*., 2021).

CHAPTER 2

# Water supply and climate change in Bulawayo, Zimbabwe

A case study of Bulawayo
by Prof Innocent Nhapi
and Dr Dube Tisetso

### 2.1.1 Geographical characteristics

Bulawayo is Zimbabwe's second-largest city and the largest settlement in the south-western region (see figure 2.1). The city sits on a plain that marks the country's highveld and is close to the watershed between the Zambezi and Shashe-Limpopo River drainage basins. Bulawayo lies on latitude S29°9" and longitude E28°58". Bulawayo is one of the two metropolitan provinces in Zimbabwe and covers an area of 1,706.8 km$^2$. The city lies in the country's south-west at an elevation of about 1,360 metres above mean sea level in a dry agroecological region whose hinterland covers the Midlands, Matabeleland South and Matabeleland North Provinces.

Zimbabwe is divided into seven hydrological catchments (see figure 2.2), which are further divided into 47 sub-catchments. Bulawayo is in the Upper Gwayi sub-catchment of the Gwayi catchment. Its climate is characterized by wide variations in rainfall and temperature, with a semi-arid climatic condition (see figure 2.3). The mean monthly temperatures range from 13.7°C to 21.8°C. Current rainfall data show that the city's mean annual rainfall is 569 mm/year with a coefficient of variation of 0.3. The city experiences three broad seasons; a dry and cool winter season from May to August, a hot dry period in early summer from late August to early November, and a warm wet period from early November to April. During the winter months, the weather is mild by day with short periods of cold nights with occasional ground frost. By being close to the Kalahari Desert, Bulawayo is vulnerable to recurrent droughts and rainfall tends to vary sharply from one season to another. Rainfall has high inter-annual variability and most of the rivers in the region are non-perennial.

Figure 2.1: Bulawayo's regional setting

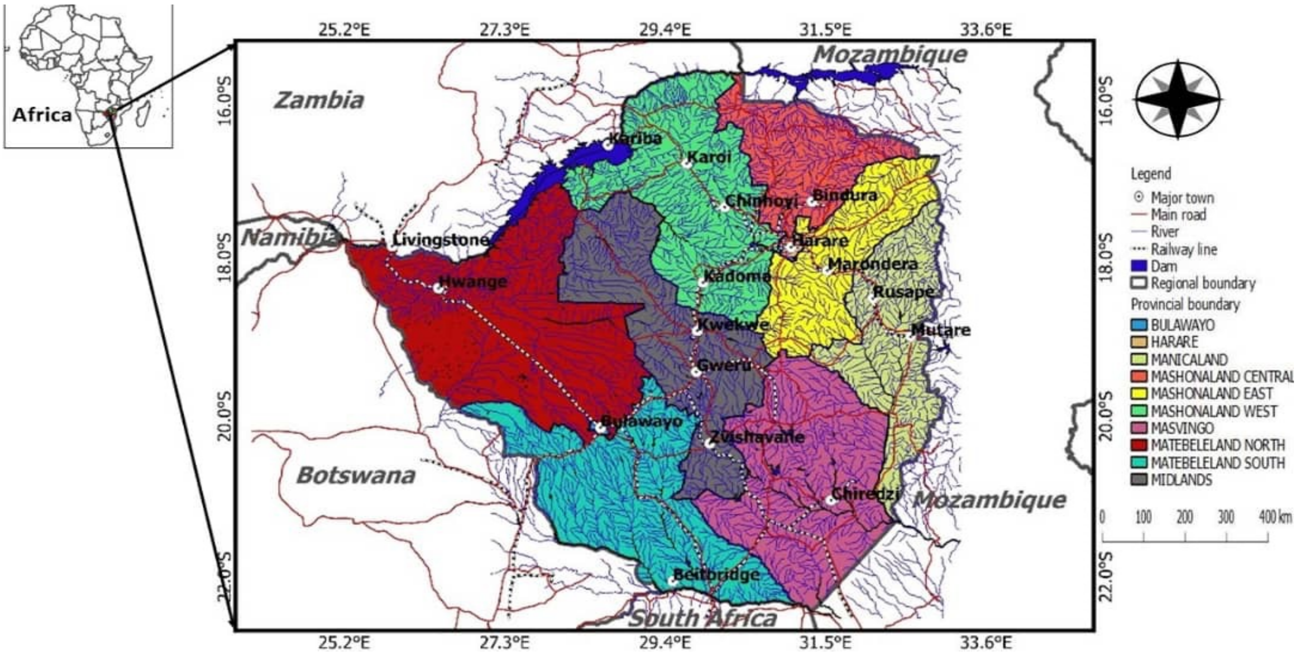



Figure 2.2: Bulawayo's location within the context of seven hydrological catchments of Zimbabwe

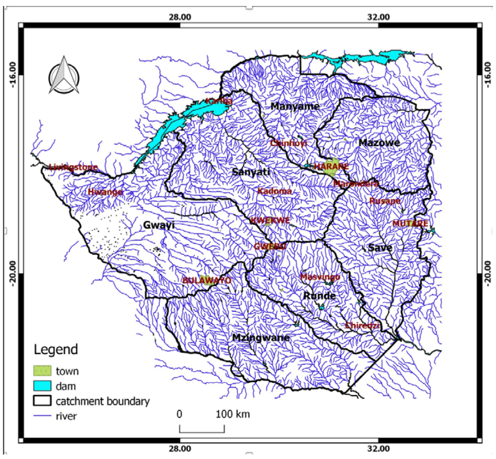
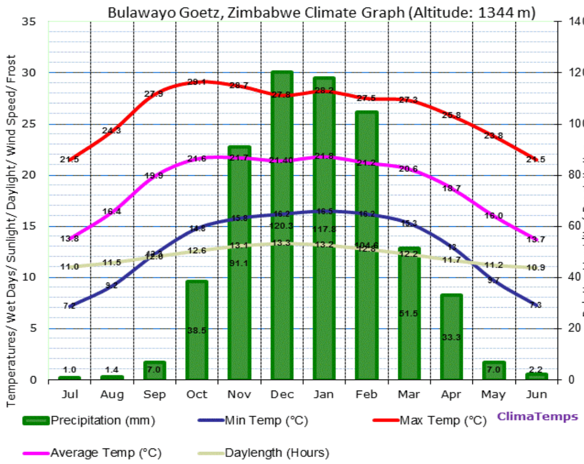
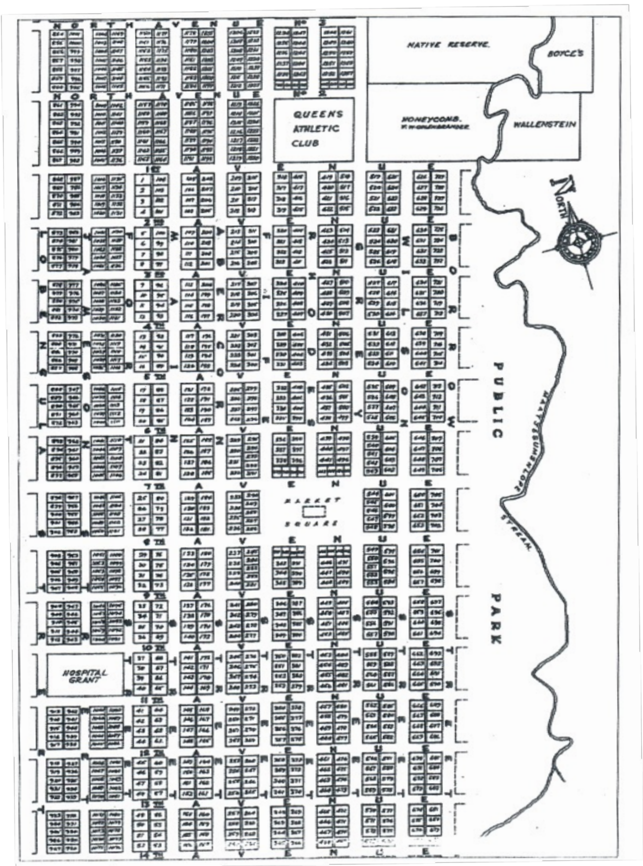



Figure 2.3: Bulawayo's average annual weather conditions



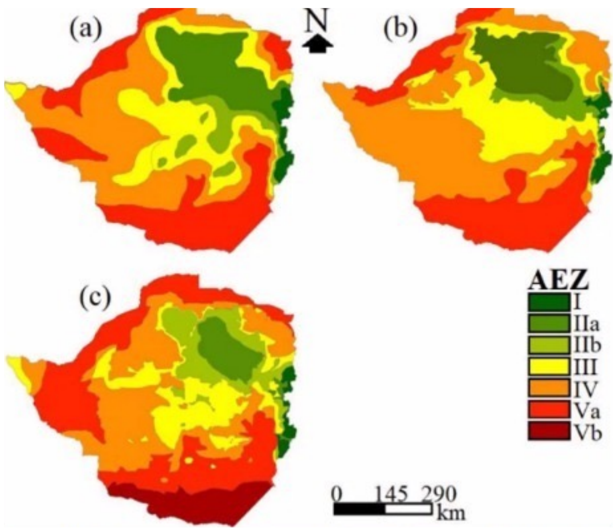

Bulawayo is strategically located. It forms the axis of a well-established air, road and rail network to the rest of the countryand to Angola, Botswana, Democratic Republic of Congo, South Africa, Tanzania and Zambia, thus developing into a major industrial, commercial, mining, ranching and tourist hub of Zimbabwe (Hamilton and Ndubiwa, 1994). Viewed as part of Cecil John Rhodes' mission to link Cape to Cairo, the construction of a railway line from the then Mafikeng in South Africa to Bulawayo in 1897 was pivotal for this initiative (Dunjey, 1994). The railway is used to service important heavy industries and food processing factories and a thermal power station (Mbiba and Ndubiwa, 2009). Over the years, many industries closed due to a decline in economic activity and water shortages, resulting in massive unemployment. In the recent past, Bulawayo had benefited from resources such as water supplies, electrical energy, food products and other consumer goods in the south-western region. The city is also a primary centre, catchment area and headquarters of the Bulawayo Metropolitan Province.

Figure 2.4: General plan of Bulawayo Township 1895–1896




Source: Ranger, 2010

Figure 2.5: Changes in agroecological zones in Zimbabwe from 1960 to 2020




Source: (a) Vincent and Thomas (1960), (b) Agritex (1984) and ZINGSA AEZ (2020)

### 2.1.2 Historical background

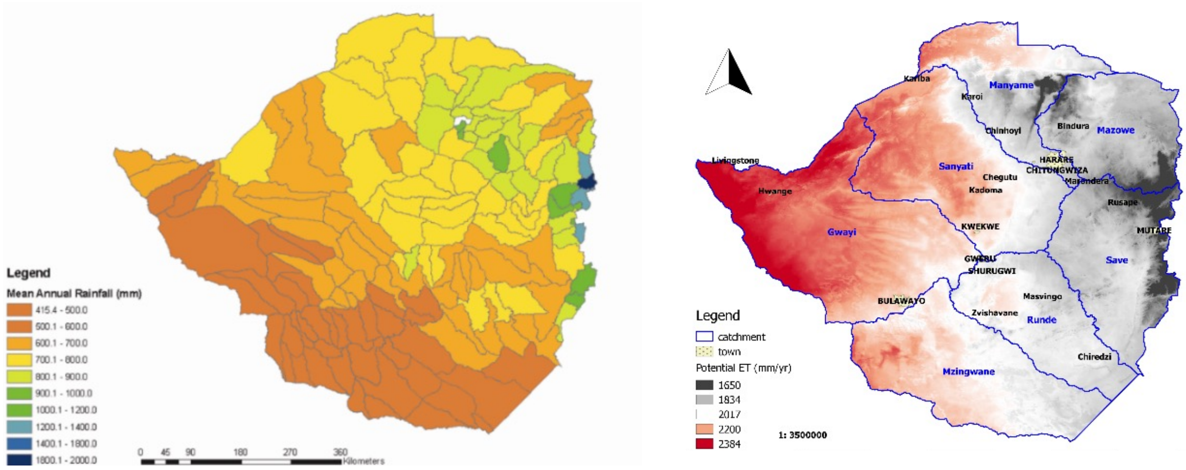
Officially founded in 1894, Bulawayo was the capital of the Ndebele State. It is one of the cities that has never had its name changed since its colonial occupation (Ranger, 2010). The name Bulawayo was given by Lobengula—the last of the Matabele kings—who chose a site for his royal kraal established on Saurdale farm, about 21 km south of the present city (Hamilton and Ndubiwa, 1994). The State House occupies a portion of land formerly occupied by members of the king's household.

The city's modern history can be traced to the 1890s when it was transformed from the Ndebele settlement of grass-thatched huts to the regional city that it is today. The city, then a collection of tents, was inaugurated in December 1893 on the site of Lobengula's royal capital after its conquest by Cecil John Rhodes' Chartered British South African Company (Official Year Book of the Colony of Southern Rhodesia, 1924). The city, with its American-inspired grid iron pattern of broad avenues and streets (see figure 2.4), was granted municipal status on 27 October 1897 and was elevated to city status under Proclamation 21 on 4 November 1943 (Council of the City of Bulawayo, 1957; Hamilton and Ndubiwa, 1994). Africans working in the town were housed in the old indigenous location now called Makokoba Township.

### 2.1.3 Impacts of climate change on Zimbabwe and Bulawayo

Like other countries, Zimbabwe is also experiencing challenges related to climate change and variability. Agroecological zones have changed (see figure 2.5) as rainfall has become more erratic. Sibanda *et al.* (2020) noted that extreme events seem to be occurring more frequently in the current century than during the twentieth. Climate change is impacting social and economic development in Zimbabwe. According to the Government of Zimbabwe, the country's economy in 2018 was largely dependent on services (61.3 per cent of gross domestic product), followed by industry (20.6 per cent), agriculture (8.3 per cent), and manufacturing (10.6 per cent). As indicated in Zimbabwe's first Nationally Determined Contribution (GoZ, 2017), the key sectors to boost the economy—such as agriculture, water, energy, forestry, tourism, and industry—are susceptible to climate variability. Natural disasters are occurring more frequently and potentially hitting the most vulnerable population, the poor, disproportionately since poor people are more vulnerable and less resilient to these hazards (ZAMCOM, 2015).

Figure 2.6: Low precipitation, high potential evapotransipiration around Bulawayo and its water supply sources




Source: ZINWA (2006) and W. Gumindoga

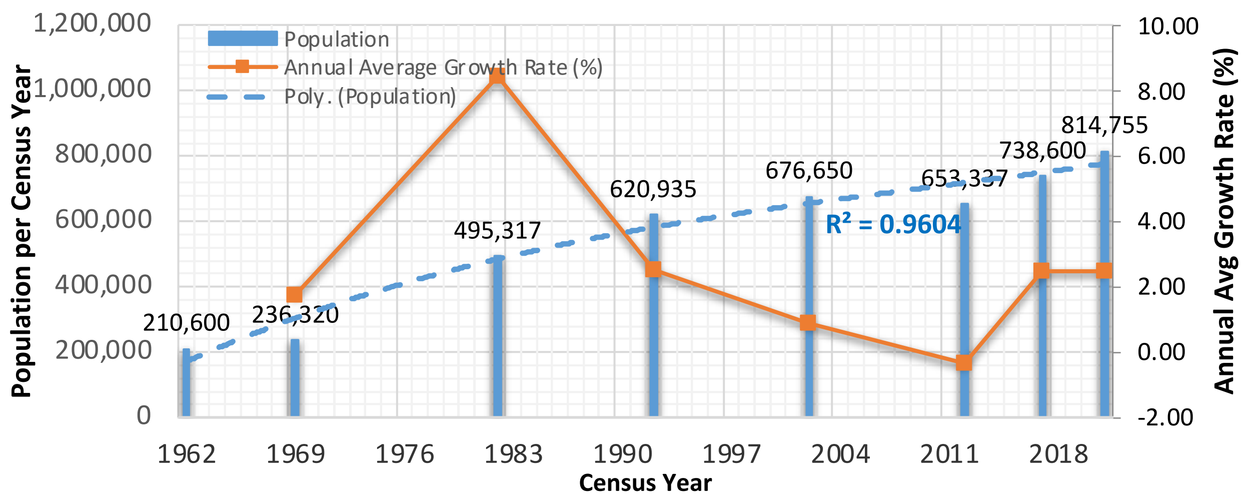
The water stress currently being faced by Bulawayo may be attributed to several factors, such as geographic location and climate-related effects (Mukuhlani and Nyamupingidza, 2014). The city's population is generally growing very fast at 2.48 per cent per annum (national average 1.81 per cent per annum); outpacing the rate of infrastructure delivery, especially water and wastewater infrastructure. This rapid urban growth is having an adverse effect on the environment and human livelihoods as it disturbs the resilience of ecosystems through deforestation, water and air pollution and depletion of the quantity and quality of the water resources (Ngwenya *et al*., 2018). This also reduces productive land for agriculture and creates unhealthy conditions, especially for the urban poor who are inadequately housed and struggle with shortages of other basic amenities like safe water and sanitation services (Brown *et al*., 2012; Dube *et al*., 2021). In 2020, the city decommissioned Umzingwane, Lower and Upper Ncema dams due to low water levels. As a result, the city remained with three supply dams (Inyankuni, Mtshabezi and Insiza Mayfair) out of the six such dams.

### 2.1.4 Primary motivation of the Bulawayo Case Study

The ability of a city to adapt and mitigate the vagaries of climate change and variability depends on several local and global factors (Grafakos *et al*., 2019). These include geographic location, land-use management, population dynamics and resilient institutions. Bulawayo lies in a semi-arid part of Zimbabwe and on a watershed. As such, dam yields are very low. Zimbabwe's mean annual precipitation is 670 mm/annum with a pronounced gradient from the drier south to the wetter north of the country (see figure 2.6). Generally, potential evaporation exceeds precipitation, with pan evaporation ranging from 1,400 mm in the high-precipitation areas to 2,200 mm in the low-lying areas. Bulawayo abstracts surface water from the Mzingwane catchment and groundwater from the Nyamandlovu aquifer. An additional surface water source is the Gwayi-Shangani Dam under construction in 2022. The Mzingwane and Gwayi catchments receive relatively low rainfall of about 500 mm/annum (Masocha *et al*., 2017). With projected decreasing total rainfall and reduced groundwater recharge (Davis and Hirji, 2014), climate change is going to seriously worsen future water availability in the city.

Some of Bulawayo's supply dams almost dry up in some seasons while the Khami Dam was decommissioned in 2012 due to excessive polluted wastewater discharges into the Umguza River. Numerous peri-urban developments are mushrooming around the city, further putting pressure on the city's water demands. Innovative and stringent water demand management measures have been implemented and local institutions have continually adapted to ensure the city remains resilient to climate change. However, despite all these challenges, the city has shown remarkable resilience and collective resolve to innovate and adapt, thus providing key lessons on water resilient development locally and in the Southern Africa region.

Figure 2.7: Bulawayo Province population trends and annual average population growth rate for 1962 to 2012, 2017 Zimstats ICDS projection and own 2021 projection




NB. Poly. (population) is the population growth trendline

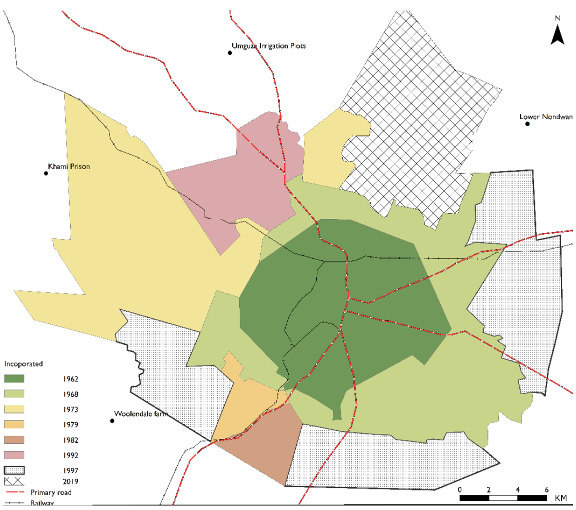
## 2.2 PROBLEM DESCRIPTION

### 2.2.1 Population growth trends and urban development dynamics

In the early 1920s, social and economic developments in Zimbabwe created a demand for labour and the need for Africans to stay in the urban areas (Schmidt, 1990). This resulted in the establishment of the first African township in Bulawayo (Makokoba) to accommodate Africans and Indians who were working in the city centre and industrial areas (Musemwa, 2003). According to Ranger (2007), the amendment of the Land Apportionment Act in 1941 made it mandatory for local authorities, railways and other corporates to accommodate the African population. Industrial developments and other centres of employment which had been established after the Second World War increased the town's demand for labour. The Natives (Urban Areas) Accommodation and Registration Act (No. 6 of 1946) obliged local authorities to finance and administer African townships and operationalize "pass laws" (Muchadenyika, 2020). This resulted in local authorities undertaking housing programmes to accommodate single men, but later developed accommodation for couples.

A trend analysis of the population growth in Bulawayo between the 1962 census and the intercensal demographic survey of 2017 is shown in figure 2.7. Additionally, figure 2.8 shows the areas of the city incorporated since 1962. The history of Bulawayo's development is summarized here from the works of authors such as Musemwa (2003, 2006), Ranger (2010), Scarnecchia (2011) and Hadebe (2015). The period between 1969 and 1974 was one of economic growth, which also experienced an increase in wage employment. The period after 1974 witnessed a decline in economic growth until independence due to the war of liberation. However, despite a decline in economic growth, there was an increase in the urban population as the war intensified and people sought refuge in cities. Since independence in 1980, the migration of the indigenous African population to urban areas increased due to the removal of "influx control"[1] legislation.

Figure 2.8: Historical development of Bulawayo incorporated areas since 1962




Source: Job Jika & Associates (2020)

The population growth rate for Bulawayo declined to 2.54 per cent for the period 1982 to 1992. Besides other factors, this also coincides with the period when HIV/AIDS started affecting the country (Sibanda, 2000). Generally, a significant proportion of the economically active population in the Matabeleland South Province migrates to South Africa and Botswana for economic reasons. As explained by Crush and Tevera (2010), the economic decline since 2000 resulted in out-migration and worsened between 2006 and 2008 when large numbers migrated to the United Kingdom, New Zealand, Australia and the United States as well as South Africa and Botswana; hence there was a population decline during that period.

The 2012 census showed that Bulawayo continued to experience a decline in population at an average annual rate of -0.34 per cent, decreasing from 676,650 in 2002 to 653,337 in 2012. This decline was also slightly felt nationally at 1.22 per cent (2002 to 2012) a slight increase from 1.17 per cent during the preceding inter-censal decade of 1992–2002. The publication of the 2012 census results has been accompanied by contestation, dissatisfaction and debate, with the city of Bulawayo disputing the results (Matamanda *et al*., 2021). Zimstats (2017) estimates that the city's population grew to 738,600 by 2017. It indicates that the city had the highest net-migration of 213.3 people per thousand in 2017 and an annual average growth rate of 2.48 per cent per annum.

### 2.2.2 Climate modelling results on Bulawayo

One of the first studies on climate modelling in Zimbabwe was done by Unganai (1996) based on twentieth century observation data and model simulations. The results suggest air temperature warming of up to 0.8°C and a decline in annual precipitation during the period 1940–1999. A more recent study on climate modelling was done by VisionRi (2019) during the preparation of the National Water Resources Master Plan; the results are shown in table 2.1 for RCP4.5 and RCP8.5. Their results show that annual average precipitation will decrease in all Zimbabwean catchments, except Mazowe and Manyame where it would remain roughly at current levels. The drier catchments of Runde and Mzingwane will be affected most, with declines in mean annual precipitation of between 12 and 16 per cent by 2050, depending on emission scenarios. Precipitation could stabilize or start to recover in the more affected catchments—Gwayi, Mzingwane, Runde, Sanyati and Save—between 2050 and 2080 if emissions are curbed, although it would continue to decline in almost all catchments if the business-as-usual emissions scenario persists. VisionRI (2019) climate modelling shows that the area where Bulawayo is located, between the Mzingwane and Gwayi catchments, will be the area in Zimbabwe  most affected by climate change. Mean annual precipitation levels in these two catchments could decrease by 12–15 per cent and 5–10 per cent, respectively, by 2050. Mean annual run-off could decline 65–100 per cent and 50–100 per cent, respectively. One of the key findings of Davis and Hirji (2014) on the Bulawayo region (Mzingwane and Gwayi catchments) is that mean annual run-off in drier southern catchments could decline significantly due to climate change.

**Table 2.1: Estimated change in precipitation, evapotranspirationand temperature for four climate scenarios for Bulawayo 2050**

| Modelling Scenario | Precipitation mm | Evapotranspiration mm/day | Temperature °C |
|---|---|---|---|
| Warm-Dry Scenario from SMHI: RCA4 driven by GCM CSIRO using RCP4.5 | 1–12 | 0.16–0.18 | 1.2–1.3 |
| Warm-Dry Scenario from SMHI: RCA4 driven by GCM CSIRO using RCP8.5 | 1–12 | 0.16–0.18 | 1.3–1.4 |
| Warm-Wet Scenario from SMHI: RCA4 driven by GCM MOHC using RCP4.5 | -9–0 | 0.16–0.18 | 1.4–1.5 |
| Warm-Wet Scenario from SMHI: RCA4 driven by GCM MOHC using RCP8.5 | -5–0 | >0.18 | 1.5–1.6 |

Source: VisionRI (2019)

**Table 2.2: Precipitation, evapotranspiration and run-off predictions for Mzingwane catchment**

| Study | Date of prediction | Mean annual precipitation (decline) | Mean annual evapotranspiration (increase) | Mean annual run-off (decline) |
|---|---|---|---|---|
| IFPRI (Zhu and Ringler, 2010) | 2030 | 13–21% | 4–6% | 19–33% |
| Zhu and Ringler (2012) | 2050 | 6–23% | 3% | 2–24% |
| Davis and Hirji, 2014 | 2050 | 12–15% | - | 65–100% |
| Sibanda et al., 2020 | 2020 | Significant spatial decrease | Not assessed | Not assessed |

Source: Southern Africa. Boulard et al., 2013; Dosio and Panitz, 2016; Moalafhi et al., 2017; Maúre et al., 2018).

None of the previous studies, for which quantitative predictions are available, covered the same area or time period as that of VisionRI (see table 2.2). The VisionRI study shows a much larger decline in run-off in Mzingwane catchment than the previous two studies by Zhu and Ringler (2012) and Davis and Hirji (2014). While the values for precipitation, evapotranspiration and run-off differ between the studies, there is a consensus that there will be a decline in mean annual precipitation and an even larger decline in mean annual run-off in this catchment by 2050. These results are consistent with the precipitation predictions from the smaller-scaled SADC modelling for Southern Africa.

Zhu and Ringler (2012) and Boulard *et al.* (2013 found that the main reduction in precipitation occurs in spring and early summer (September to December) in the Mzingwane catchment. Another study in this catchment found that the main reduction in precipitation would occur in the dry months of early April to September (Sibanda *et al*., 2020). River flow in Gwayi and Mzingwane catchments could decline significantly if greenhouse gas emissions are not controlled (the business-as-usual scenario). The Mzingwane catchment will possibly experience major declines in groundwater recharge by 2050 and 2080 as predicted by Davis and Hirji (2014). General principles suggest that dambos, shallow hard-rock aquifers and other unconfined aquifers that receive direct recharge are likely to receive considerably less than at present.

### 2.2.3 Hydrological basin rainfall

**Rainfall and temperature trends for the subregion**

The primary factors that influence water availability are precipitation, evaporation and evapotranspiration (governed by solar radiation, temperature, wind and vegetation cover). Regarding rainfall, concerns are not just about its quantity, but also about precipitation distribution over the year, duration, intensity of showers and rainy periods (Aguilar *et al*., 2009). Some of these factors have been elaborated below for Bulawayo and its water supply catchment.

El Niño Southern Oscillation (ENSO) phenomenon, which is triggered by changes in sea surface temperatures, has significant implications for rainfall across Zimbabwe (Lesolle, 2012). The country tends to receive less than average rainfall during the warm phase of ENSO (or El Niño); and more than average rainfall during ENSO's cool phase (or La Niña); Hoell *et al*., 2021. Drought conditions during the 2015-2016 rainfall season also aligned with El Niño's warm phase (World Bank, 2021). The comparative historical climate data for Zimbabwe and Bulawayo between 1901 and 2020, as shown in table 2.3, confirm that Bulawayo is in a semi-arid part of Zimbabwe.

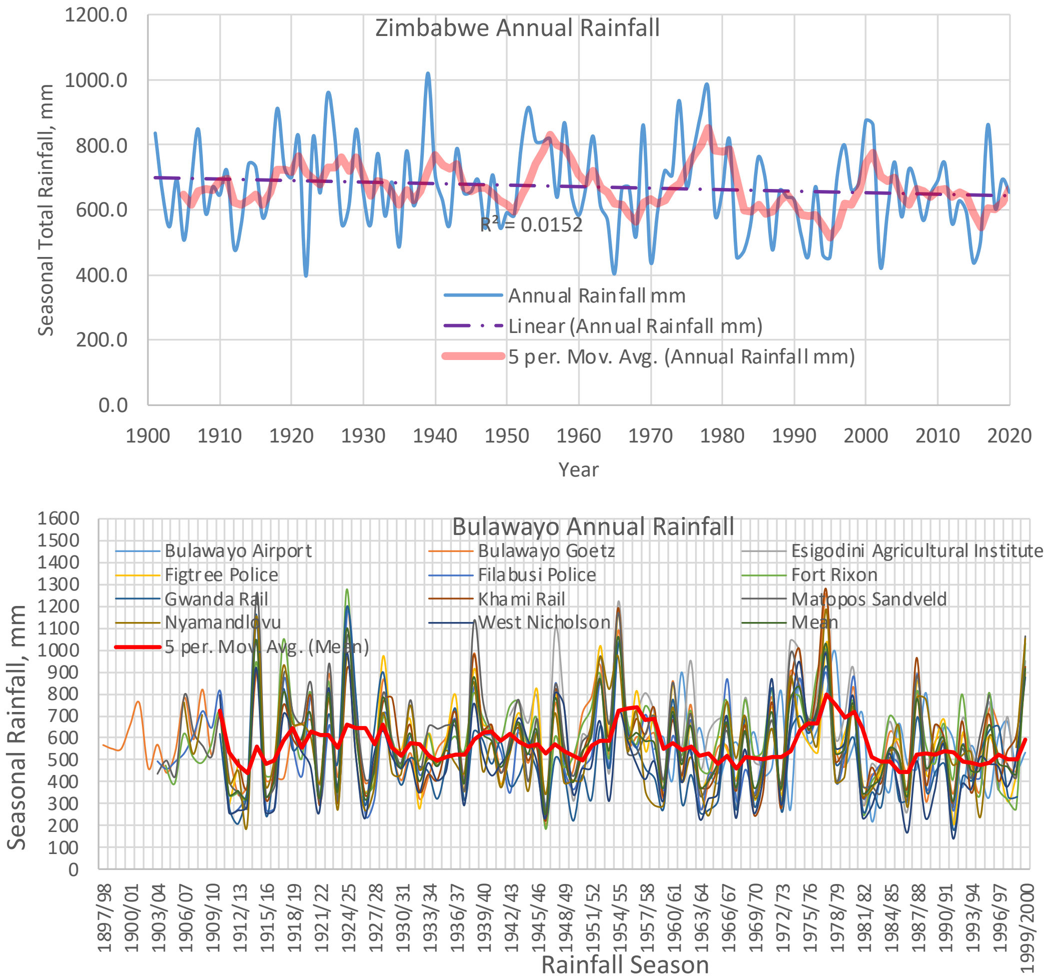
The mean annual precipitation for Bulawayo for the period since 1901 (see figure 2.9) exhibits an insignificant decreasing trend for all stations, in line with national trends. Detailed studies by Sibanda *et al*. (2020) in the Mzingwane catchment, Mazvimavi (2010) across

**Table 2.3: Historical climate data for Zimbabwe and Bulawayo for various periods between 1901 and 2020**

| Climate Variables | Zimbabwe 1901–2020 | Bulawayo 1910–2020 |
|---|---|---|
| Annual Temperature (°C) | 21.2 | 18.9 |
| | (20.6–21.9) | |
| Annual Min-Temperature (°C) | 15.5 | 7.0 |
| | (14.5–16.5) | |
| Annual Max-Temperature (°C) | 25.0 | 29.0 |
| | (24.2–25.9) | |
| Annual Precipitation (mm) | 670.4 | 568.5 |
| | (486.6–849.3) | (353.2–804.7) |

Source: Bulawayo data. Bulawayo Goetz Climate & Temperature. Available at http://www.bulawayo-goetz.climatemps.com/
Note: The medians (50th percentile) are highlighted in bold font, while the 10th and 90th percentiles are presented in parentheses.

Figure 2.9: Mean annual rainfall for Zimbabwe compared with rainfall stations around Bulawayo since 1901




Source: Meteorological Service Department

Figure 2.10: Mean temperature variations for Zimbabwe (1901–2020)

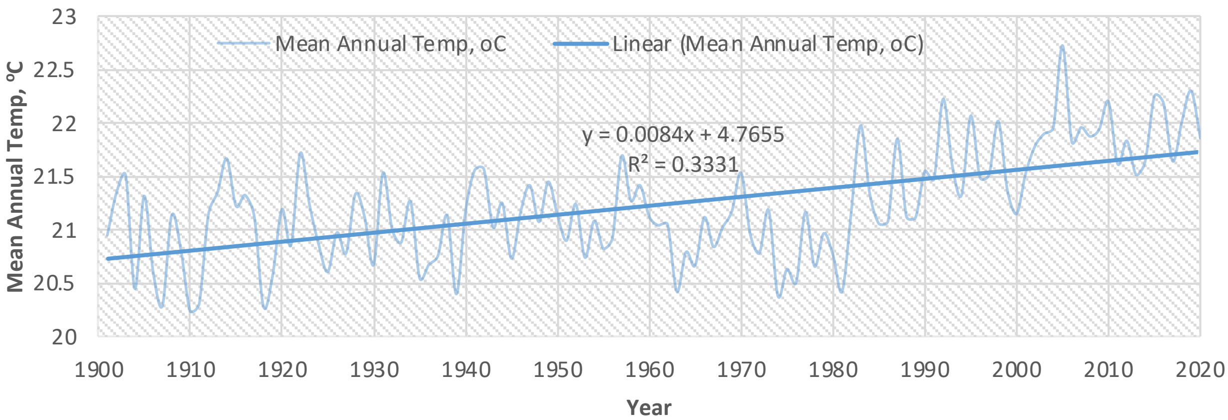
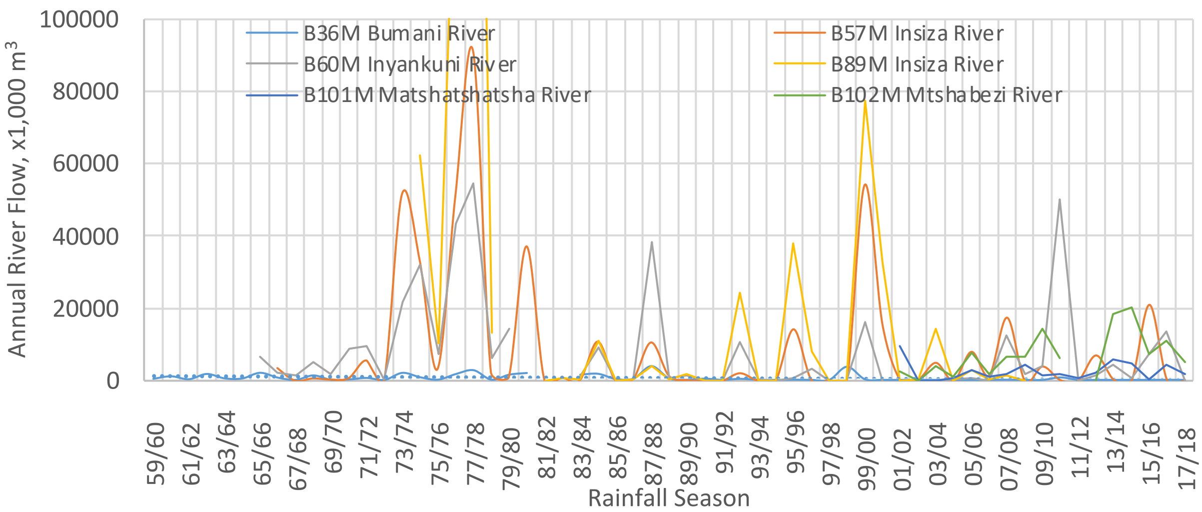



Figure 2.11: Stream flow variations recorded 1960–2017 for rivers flowing into Bulawayo supply dams



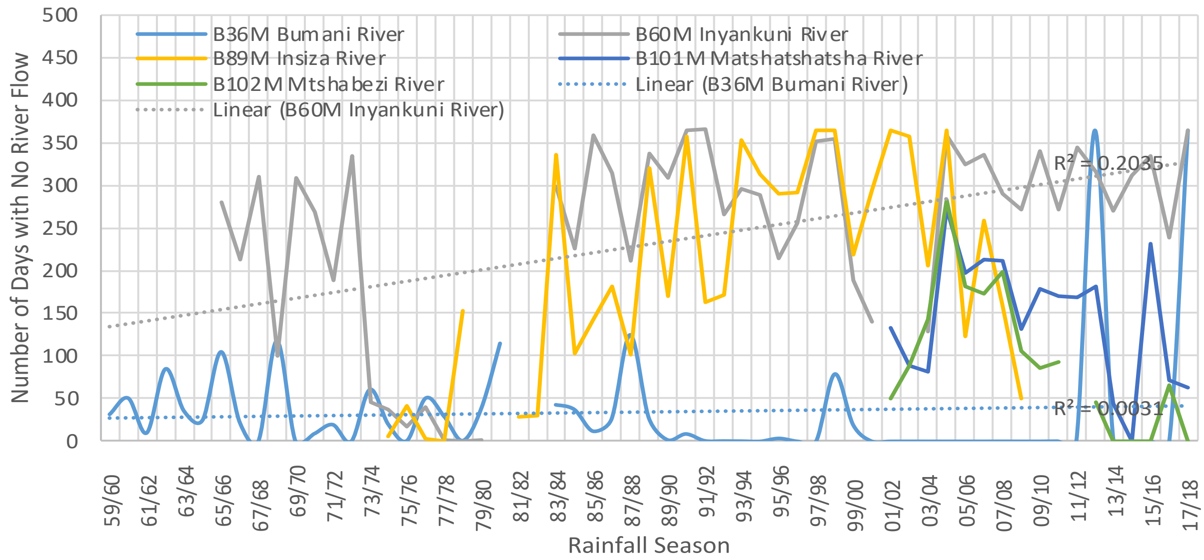

40 Zimbabwean stations between 1892 and 2000 and Muchuru *et al*. (2016) for the Kariba catchment area of the Zambezi River basin, reported statistically insignificant decreasing rainfall trends. These findings confirm that rainfall quantity in Zimbabwe has not changed significantly despite global climate warming.

Moyo *et al.* (2005) noted that Bulawayo dam yields had declined from 131.3x10$^6$ m$^3$ in 1980 to 67.90x10$^6$ m$^3$ in 2005, suggesting that the impact of climate change and variability in southern Zimbabwe may be higher than predicted by global models. Figure 2.10 suggests that the mean annual temperature in Zimbabwe has increased by roughly 0.08°C per decade from 1901 to 2020. The impact of the warming trend on the intensification of the droughts is greater during the January-March period (GoZ, 2016). The maximum temperature trend shows a warming trend at a rate of 0.05°C/decade, while minimum temperature shows a warming trend of 0.11°C/decade. This implies that winter seasons are becoming warmer and the rate of increase is higher than that of maximum temperatures.

## Run-off flow patterns

Using data from the time of construction, there have been noticeable decreases in the amplitude of the run-off peaks into the Bulawayo supply dams since 1960 (see figure 2.11). After the 1979/80 hydrological year, there was a sudden change in the pattern and the number of recorded no-flow days increased slightly as shown in figure 2.12. From that season, there was an increase in the duration and number of drought years. As the inflows into a reservoir directly affect its yield, Moyo *et al*. (2005) say there should be a corresponding decrease in the reservoir yields.

Figure 2.12: No-flow days for some Bulawayo water supply dams

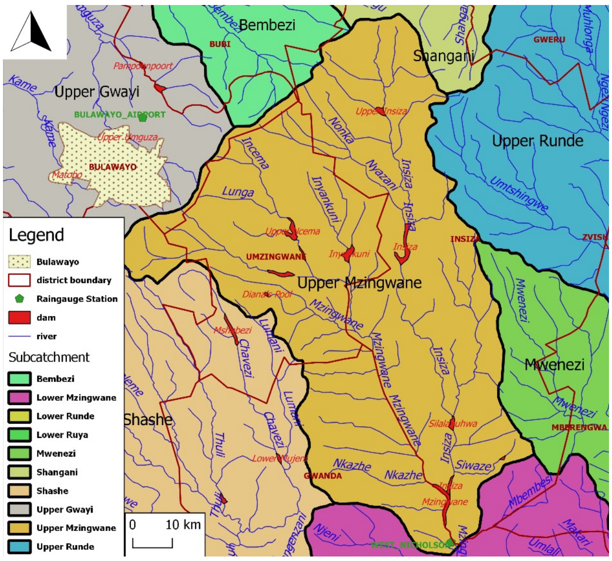



## 2.2.4 Water resources: dams and aquifer levels

### Dam water level patterns

Bulawayo is served by surface and groundwater sources. However, the main sources are six dams built between 1958 and 1994 in the Mzingwane catchment (see figure 2.13 and table 2.4). The dams are the Umzingwane, the Inyankuni, the Insiza, the Mtshabezi, Upper and Lower Ncema. Khami Dam, which is at the north-western end of the city, was decommissioned in 2012 due to high pollution levels. Water supply from the dams has generally declined, due to drought and

Figure 2.13: Watersheds of current supply dams for Bulawayo




decreased run-off. Excluding Insiza Dam, which is 20.5 per cent Government-owned, all the dams, conveyance systems and purification works are owned by the city of Bulawayo. The total estimated yield from the supply dams is 167,400 m³/d, based on a 4 per cent risk yield (96 per cent assurance level). Other studies have estimated yields ranging from 74,000 to 192,000 m³/d (GKW Consult, 1988; SWECO, 1997; Abaziyo-Ziyanda, 2012; Bosch Stemele, 2012). ZINWA should be the authority on yield estimates but its figures range from a recent estimate of 73,685 m³/d to 169,346 m³/d (ZINWA, 2012; Abaziyo-Ziyanda, 2012). Water supply system safe yield changes over time depending on storage and hydrologic characteristics (rainfall/run-off/evaporation) of the sources, the source facilities, upstream and downstream permitted withdrawals and minimum in-stream flow requirements (Kabell, 1974; Leib and Stiles, 1998; Zeraebruk et al., 2017). The yield of 167,400 m³/d is less than the current demand of 231,000 m³/d as evidenced by severe water shortages in extended drought periods. Bulawayo has been forced to ration water periodically for several years since 1976 (Norplan, 2001; Bosch Stemele, 2012).

The water level fluctuations in Bulawayo's supply dams shown in figure 2.14 is consistent with the rainfall and river flow patterns. Basing on records from time of construction of each dam, Mzingwane has averaged 40 per cent full capacity, Insiza 57 per cent, Inyankuni 38 per cent, Lower Ncema 55, Upper Ncema 29 per cent and Mtshabezi 90 per cent. These low dam capacities have a serious impact on water security in the region - a situation that will be worsened by climate change.

**Table 2.4: Details of main water sources for Bulawayo**

| Name of Supply Source | Year Commissioned | Catchment Area, km² | Evaporation (mm/year) | Mean Annual Run-off (mm) | Mean Annual Rainfall (mm/year) | C.V. Rainfall | Capacity ($10^6$ m³) | Dam Storage Ratio | 4% Risk Yield (m³/day) |
|---|---|---|---|---|---|---|---|---|---|
| Umzingwane Dam | 1958 | 407 | 1 409 | 83.2 | 629 | 0.35 | 44 660 | 1.30 | 35 300 |
| Inyankuni Dam | 1964 | 352 | 1 836 | 37.4 | 618 | 0.35 | 81 800 | 6.21 | 20 800 |
| Upper Ncema Dam | 1973 | 643 | 1 389 | 70.9 | 633 | 0.35 | 45 460 | 1.00 | 42 500 |
| Lower Ncema Dam | 1943 | 713 | 1 389 | 70.9 | 633 | 0.35 | 18 240 | 0.36 | |
| Insiza Dam | 1976 | 1 800 | 2 004 | 30.4 | 611 | 0.34 | 176 000 | 3.30 | 33 700 |
| Mtshabezi Dam | 1994 | 205 | | | | | 51 996 | | 17 200 |
| Khami Dam | 1928 | | | | | | Decommissioned in 2012 | | - |
| (Insiza Dam?) | | | | | | | | | 17 900 |
| Nyamandhlovu (Rochester) 56 Boreholes | | | | | | | | | 9 000* |
| Nyamandlovu Epping Forest 21 Boreholes | | | | | | | | | 10 000* |
| Total | | | | | | | 418 156 | | 186 400 |

Source: Bulawayo City Council, Bosch Stemele, 2012; ZINWA database and various studies

## Aquifer water level patterns

Bulawayo is also supplied by 77 boreholes from the Nyamandlovu aquifer, about 60 km north-west of the city, with a potential total capacity of 26,000 m³/day and safe yield of 19,000 m³/d. Fifty-six boreholes were installed during the severe drought of 1992 and were not fully operational until 2012; another 21 boreholes were drilled in 2020. The water is pumped into a common supply pipeline that feeds into the Rochester Reservoir where the responsibility of ZINWA ends and the city council takes over the distribution function.

The Nyamandhlovu aquifer lies on the edge of the Kalahari sedimentary basin. In some places, thin patches of Kalahari aeolian sands cover Karoo basalts, and the basalts overlay the forest sandstone, which rests directly on the granitic gneiss basement complex (Gwaze *et al.*, 2000; Rusinga and Taigbenu, 2005). Figure 2.15 shows the distribution of the 14 monitoring boreholes in the Nyamandhlovu aquifer, together with the aquifer outcrop extent. Some of the monitoring results are shown in figure 2.16. On average the water levels have declined between one and five metres, with an average decline of 2.65 metres over 22 years between 1989 and 2012 (VisionRI, 2019). There are also many small private boreholes scattered around Bulawayo. A Nyamandhlovu aquifer study by Sibanda (2006) established an average recharge rate of 25 mm/year, representing 4.5 per cent of the long-term average annual rainfall of 555 mm with total direct and indirect recharge into the aquifer of 36.9 Mm³/year.

Figure 2.14: Capacity fluctuations for Bulawayo supply dams since 1970

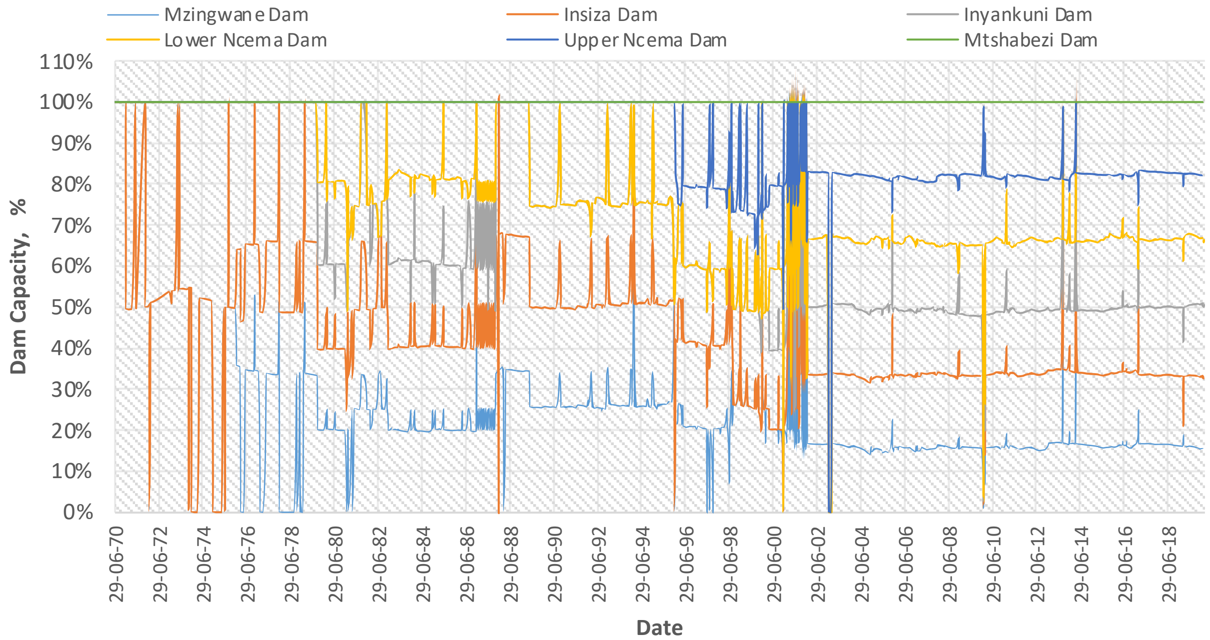



Figure 2.15: Geology of Nyamandhlovu aquifer and location of some monitoring boreholes

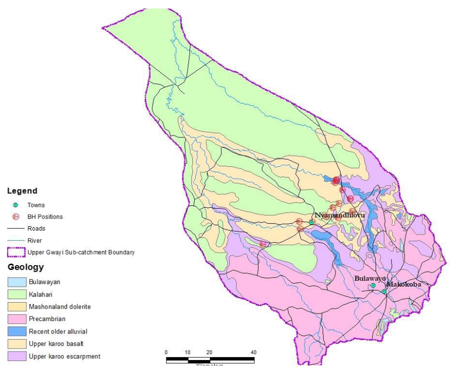
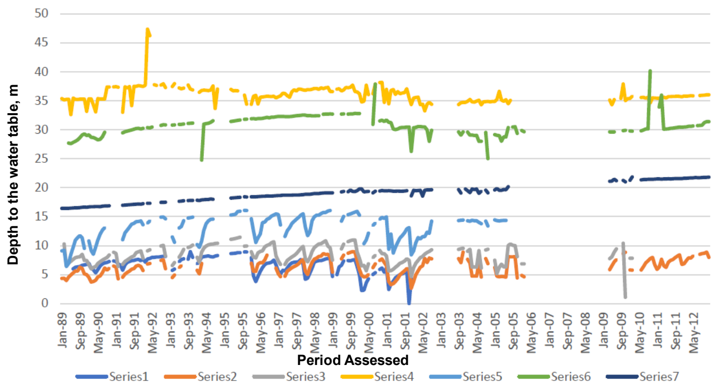



Figure 2.16: Borehole water level fluctuations in Nyamandhlovu aquifer – 22-year period



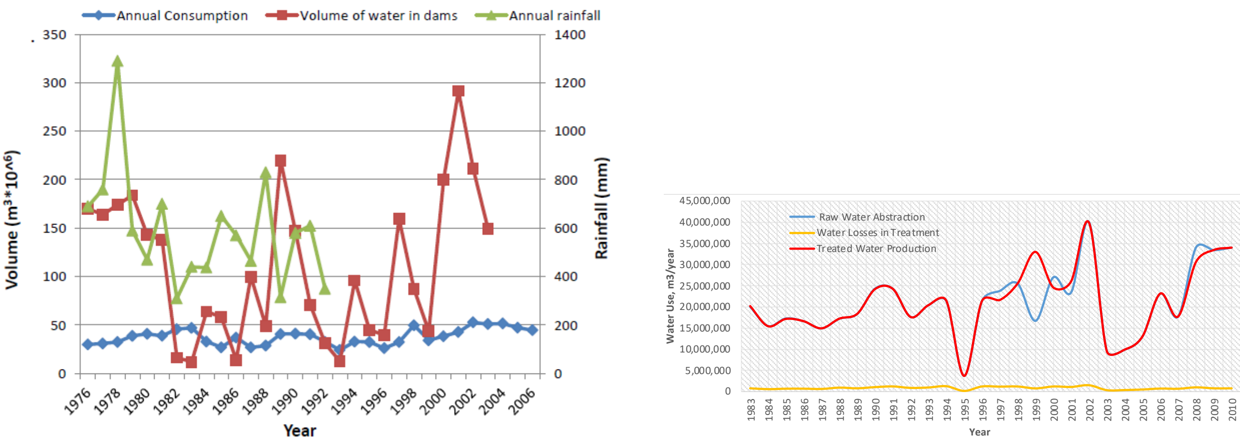

Source: Owen (2016)

## 2.2.5 Water demand and supply network

### Historical perspective of water supply

The water demand for Bulawayo, inclusive of losses, was estimated at 100,000 m³/day in March 2000 (Norplan, 2001). The *Bulawayo Matabeleland Zambezi Water Supply Feasibility Study* by SWECO (1997) estimated the suppressed consumption in 1996 at 30 per cent. In the revised project request for the *Bulawayo Water Conservation and Sector Services Upgrading Project* dated February 1998, the unrestricted demand was estimated to be 185,000 m³/day. Based on Abaziyo-Ziyanda (2012), figure 2.17 depicts the trend of water abstraction and supply from 1983 to 2010, despite some data inconsistences. The recent data from the city council had more gaps and inconsistencies and was not used. Though the city's population is growing, the water supplied to it has not grown much and remained at 71,682±20,995 m³/d. This implies that the per capita

Figure 2.17: Raw water abstraction, treated water production and water losses during operation in Bulawayo 1983–2010




Source: Abaziyo-Ziyanda (2012) and BCC records

water use has been reducing as the population has been growing. It should also be noted that these figures are under the strict water demand management conditions (including rationing and restrictions) that the city already has in place most of the time.

### Current and future water demand

This study used the unit water consumption figure of 170 litres per capita per day (L/cap.d) based on a combination of Bulawayo Service Level Benchmarking (SLB) figures (175 L/cap.d), national average SLB figures (205 L/cap.d) and SLB benchmark of 150 L/cap.d. Also used are figures by Norplan in the 2001 study for 1980–1999 (98 L/cap.d) and the VisionRI (2019) figure of 200 L/cap.d for large urban areas. The SLB figures are based on final water production at the treatment plant, so they only exclude about 10–15 per cent of water lost during water treatment. The benchmarking project was a national performance assessment system by urban local authorities based on an annual peer review. The water demand for industries, institutions, commercial activities and water losses was taken into account as a percentage of the average per capita demand adopted for the urban areas. The water consumption by category for the period 1980/81 to 1994/95 was examined in the Bulawayo-Matabeleland Zambezi Water Project report (SWECO, 1997). The average contributions for the period were noted as follows: domestic low and high density 60 per cent; industrial 13 per cent, commercial 6 per cent and institutional 21 per cent. Assuming that this normal pattern will return in the future, this was used to estimate water demand in figure 2.18 for the years to 2052, based on population projections by the Zimbabwe Statistical Agency, ZimStats.

Based on the present and projected future water demands for Bulawayo in figure 2.18, it can be concluded that the present water supply capacity of 186,400 m$^3$/d is already below the current water demand of 230,847 m$^3$/d in 2021. This strongly justifies current efforts to speed up the construction of the Gwayi-Shangani Dam and its pipeline link to Bulawayo. Figure 2.19 shows that the first stage of this pipeline should be able to augment the city supplies for the next 20 years and the second pipeline should be able to take the city to just around the year 2070, after which additional supplies from the Zambezi River will be required. Climate change and unrestricted water consumption levels could bring these timelines forward.

## 2.2.6 Current water supply system

A schematic of the water supply system in Bulawayo is shown in figure 2.20. Bulawayo has treated water storage and distribution reservoir facilities totalling 401,000 cubic metres a day (m$^3$/d) capacity, excluding Ncema Water Treatment Works and the booster pump stations at Fernhill and Cowdray Park (Abaziyo-Ziyanda, 2012). Basing on the 2021 estimated demand of 237,000 m$^3$/d, this is equivalent to approximately 1.69 days of storage. When the Ncema Water Treatment Works is taken

Figure 2.18: Bulawayo water demand forecast (in m3/d) in comparison with current and previous studies

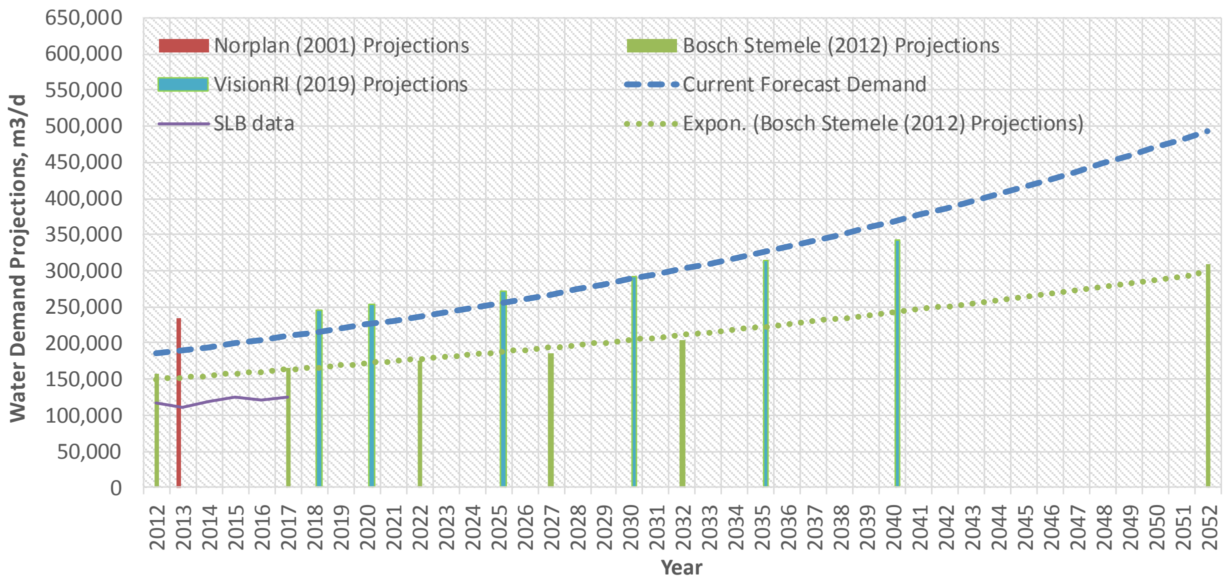
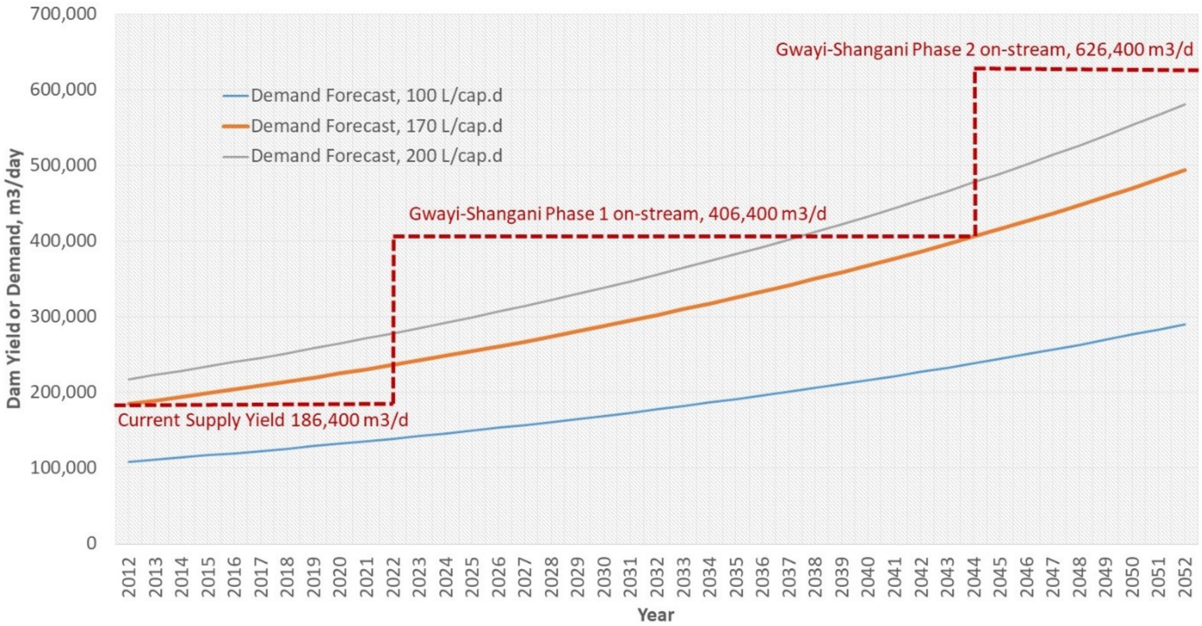


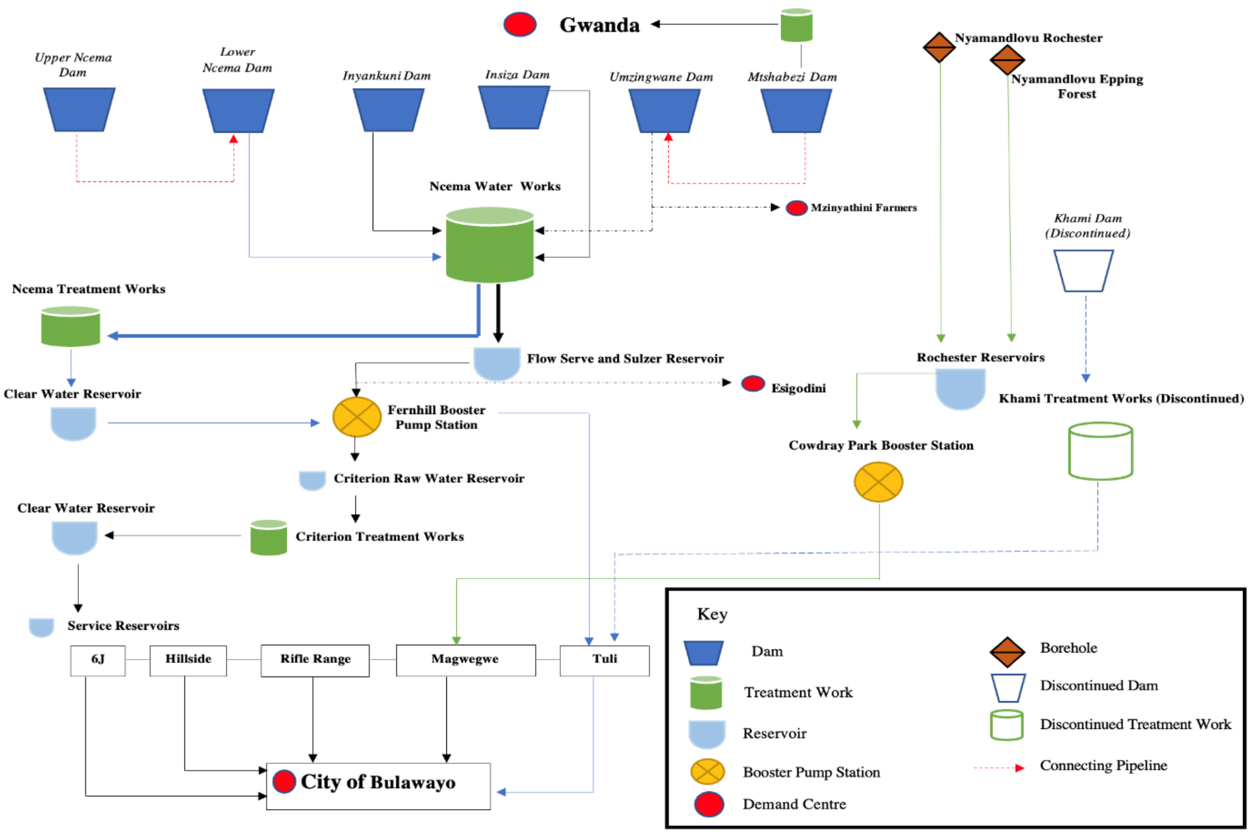

Figure 2.19: Water demand (m3/day) development for different growth and water consumption scenarios




into account, the available storage capacity is 408,400 m³/d, which is equivalent to approximately 1.73 days of storage. Using a minimum storage provision of 48 hours (Davis, 2020), it is observed that Bulawayo should consider augmentating the storage facilities in the short to medium term.

Bulawayo has a water treatment capacity (via the Ncema and the Criterion Water Treatment Works) of 261,000 m³/d; which is only sufficient until 2026 in the medium scenario of 170 L/cap.d, or 2040 under very strict rationing of 100 L/cap.d. The city can convey surface raw water from sources to water treatment works of 181,500 m³/d when all sources are in use. This reduces to a capacity of 127,000 m³/d when the Umzingwane and Inyankuni Dams are decommissioned. In both these cases, the raw water infrastructure is inadequate for current and future demands and needs to be augmented.

Figure 2.20: Schematic for the current water supply system in Bulawayo



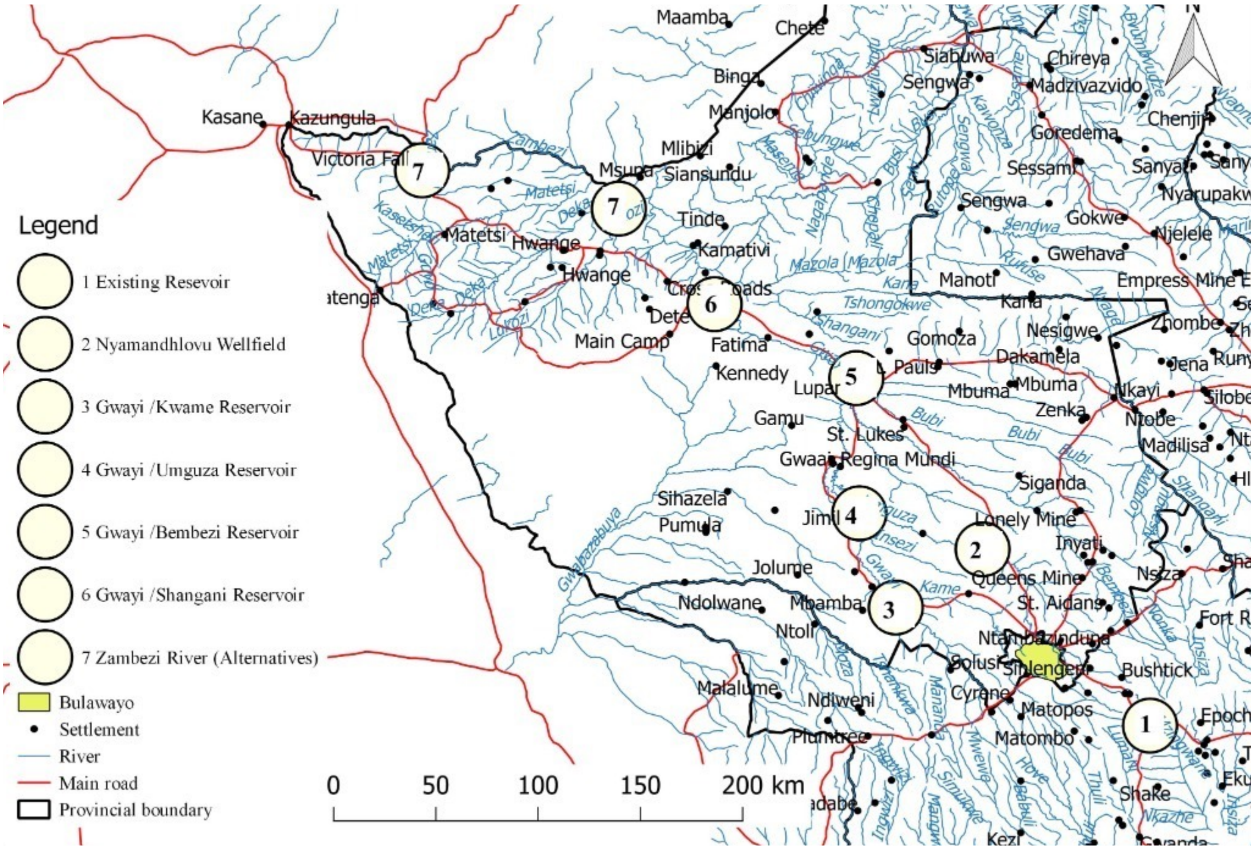

## 2.3. ACTIONS TAKEN

### 2.3.1 Bulawayo water supply improvement plans

The city has been constantly involved in projects to improve its water supply. These include efforts to optimize current supplies and develop new water sources. In 2016, a pipeline link from the Mtshabezi Dam, with a yield capacity of 17,200 m³/d, was commissioned. Recently commissioned is an additional supply of 17,900 m³/d from Insiza Dam, the largest of the existing dams. Insiza had been a reliable source of raw water supply to the city during severe drought years when the other dams could not provide their safe yields.

There are concrete plans under way to augment Bulawayo's water supply through the Gwayi-Shangani Dam within the coming 1–3 years. The dam is about 240 km to the north of the city (see figure 2.21). The supply will have a reservoir to receive raw water and treatment works at Cowdray Park. Considering that the Gwayi-Shangani Dam and the subsequent Zambezi link are the ultimate long-term water sources for Bulawayo, the pipeline was sized to convey the 4 per cent risk yield of 440,000 m³/d for the Gwayi-Shangani Dam. To convey this, 2No. x 1,200 mm diametre pipelines are required, each conveying 220,000 m³/d (or 2.55 m³/s) at a maximum flow velocity of 2.251 m/s. However, for the project to be viable, the pipelines will be constructed in two phases; corresponding to Bulawayo's water demand. In the current first phase, 1No.x 1,200 mm diametre pipeline shall be constructed. The booster pump stations are designed to accommodate pumps and break-pressure tanks for both pipelines but in such a way that construction can also be done in two phases. Each pipeline shall have three pump sets - two on duty and one on standby. Therefore, for both pipelines a total

Figure 2.21: Current and proposed water sources for Bulawayo, including Gwayi-Shangani Dam (in 2022) under construction



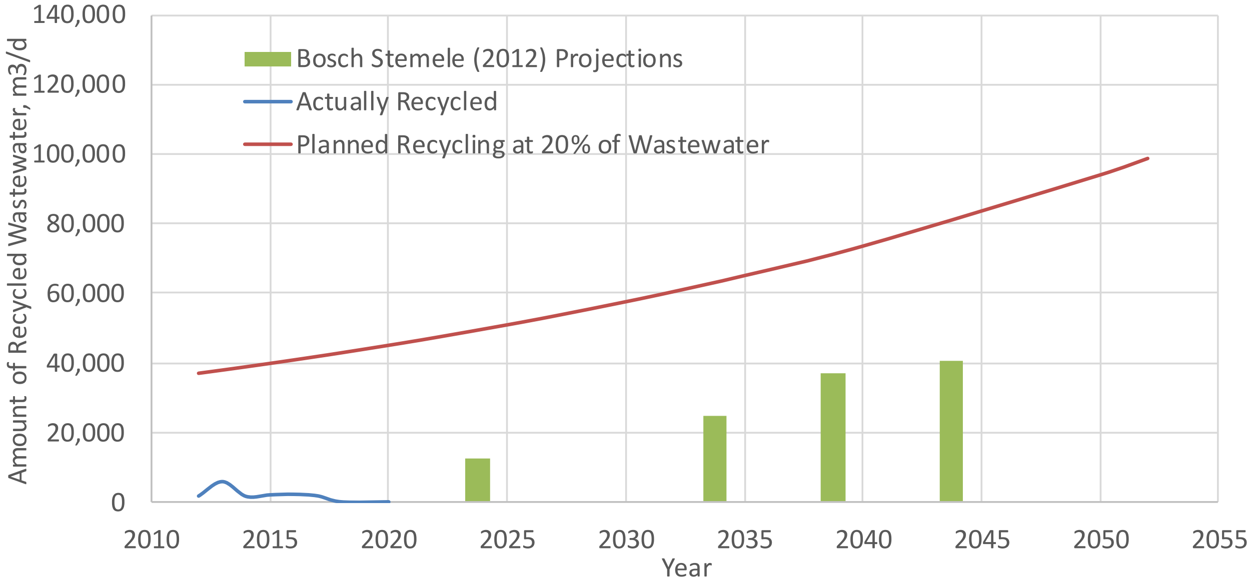

of six pump sets are required, each one with capacity to pump 1.275m³/s. This is a critical lifeline for Bulawayo's water supply requirement, and will provide the maximum security of supply. The pipeline will see communities along the way benefitting through pipeline offtakes for irrigation.

The 2012 Water and Wastewater Master Plan provides an elaborate course of action for Bulawayo but implementation is currently hampered by the lack of resources. The projected developments will result in an increase in water demand of up to 288,000 m³/d by the year 2030 and 368,000 m³/d by the year 2040. To manage this situation, the following proposals, modified from Bosch Stemele (2012), are suggested:

- 65 per cent of the bulk water supply in 2030 will be provided from existing water sources with a yield of 186,400 m³/d, from the Mtshabezi pipeline and boreholes from the Nyamandlovu aquifer schemes.
- 35 per cent of the bulk water requirement in 2030 would be provided from the Gwayi-Shangani Dam. This proposal would cater for water demand of the Magwegwe Reservoir, Cowdray Park and proposed future northern reservoirs.
- In 2040, the supply between the existing scheme and the proposed Zambezi and Gwayi-Shangani Dam will be 50 per cent each, implying that the second pipeline from Gwayi-Shangani Dam to Bulawayo should already be under construction by then.

The other proposed strategies for ensuring the security of bulk water supply—which include leakage reduction, recycling of wastewater and development of groundwater supplies—would need to be pursued in the short to medium term until the Zambezi/Gwayi-Shangani pipeline is implemented. According to SWECO (1997) and Bosch Stemele (2012), 20 per cent of the total water demand requirement for Bulawayo was proposed to be met by

Figure 2.22: Current wastewater recycling and projections for meeting at least 20 per cent of future water demand through wastewater recycling




recycling treated domestic sewage for potable reuse, as well as for non-potable reuse in industry, parks and gardens. The target of 20 per cent is considered to be a reasonable proportion to provide sufficient dilution of approximately 1:5 for recycled wastewater to conventionally treated raw water (National Research Council, 2012). The city records show that, currently, about 12 per cent of wastewater produced is being recycled for non-potable uses by the city council, industries and Zimbabwe Power Company. Based on the above and taking into consideration the present and projected future water demands in this study, the revised targeted required volumes of recycled water are indicated in figure 2.22. The Bosch Stemele (2012) projections are based on very conservative estimates and are generally 64 per cent of current projections. The development of the required recycling infrastructure can be phased based on projections for 2030, 2040 and 2050.

Mutengu *et al.* (2005) carried out a study in Bulawayo to assess the potential health impacts of effluent reuse for irrigating crops. The results show that 70 per cent of the respondents were aware of the related health risks of using wastewater for irrigation but no major disease outbreaks were reported. The safety and acceptability of wastewater reuse by communities in Bulawayo is key to the uptake of direct potable wastewater reuse, which is being adopted by fellow semi-arid cities like Gaborone, Botswana, and Windhoek, Namibia.

### 2.3.2 The spatial dimensions

**Efforts to boost current surface and groundwater supplies**

Over the past 30 years, Bulawayo has carried out several projects to boost supplies, as indicated and analysed in table 2.5.

In addition to the projects that have been implemented already, the city council, in close collaboration with ZINWA, has a number of planned projects to boost water supplies, as shown in table 2.6.

**Water Demand Management**

The success of water supply in Bulawayo under a constrained supply regime may be attributed to demand management in its various forms. The major water demand management actions per development/land-use category are summarized in table 2.7. In general, these have managed to keep water use within 40–60 per cent of the unrestrained water demand of ≥200 L/cap.d.

### 2.3.3 Institutional framework for water supply and climate change adaptation

Zimbabwe is a signatory to multilateral environmental agreements such as the United Nations Framework Convention on Climate Change, the United Nations Convention to Combat Desertification, and the United Nations Convention on Biological Diversity. The Ministry of Environment, Climate, Tourism and Hospitality is

**Table 2.5: City-implemented infrastructure projects to enhance water supply and their implications**

| Year Executed and Project Name | Description and Spatial Planning Aspects | Implications of the Action |
|---|---|---|
| 1993 – Nyamandlovu aquifer boreholes | A total of 56 boreholes drilled at Rochester to supply 16,000 $m^3$/d to the city | Helped to boost water supplies when dam levels were very low due to the 1992 drought |
| 2016 - Mtshabezi Dam link | 42 km pipeline link to Mzingwane Dam | Boosting city supplies with additional 17,200 $m^3$/d |
| 2020 - Nyamandlovu Epping Forest boreholes | Drilling and equipping of 21 boreholes, construction of 2,280 $m^3$ storage tank, highlift pumphouse, supply pipelines and ancillary works at Epping Forest to add 10,000 $m^3$/d to the city | Existing supplies of 176,400 $m^3$/d boosted by 6% at a cost of USD 5.2 million |
| 2016–2022 - Construction of Gwayi-Shangani Dam | Construction of dam and commencement of the pipeline link to Bulawayo | City supplies to be boosted by additional 220,000 $m^3$/d, greatly improving supplies for the next 20 years or so. |
| 2021 - The rehabilitation of raw water pump stations | The raw water pumping stations at Ncema and Fernhill were rehabilitated | Improve water supplies |
| 2021 - The WO1 programme | Tracking and fixing non-revenue water | Reduce non-revenue water and improved operational efficiency |

### Table 2.6: Planned projects to improve water supplies in Bulawayo

| Project Name | Status |
|---|---|
| Duplicating the Mtshabezi link to Umzingwane in an effort to maximize abstraction so that water may gravitate from Umzingwane as currently the local authority is pumping. | Not yet done |
| Duplicating pipeline from Mzingwane to Ncema | Not yet done – detailed feasibility study required |
| Duplicate Inyankuni to Ncema so as to maximize on abstraction | At proposal stage – intention to have a design and construction tender. Not much detail available |
| Mtshabezi-Ncema pipeline design and construction of 600 mm water pipeline | Not yet done |
| Umzingwane-Ncema design and construction of a 900 mm water pipeline, 11 km long | At proposal stage – requires funding for design and construction |
| The recycling of water at the Southern Area Sewage Treatment Works and Khami water works. This includes the rehabilitation of sewer lines feeding the plants, completing outstanding engineering works, installing and upgrading pumps and pipes to mix in water from below Khami dams, processing the water, collecting it after treatment works and piping it 21 km to Criterion. | Feasibility study in limbo following the suspension of the contract for a detailed feasibility study under Bulawayo Water Supply and Sanitation Improvement Plan. |
| Expansion of the Nyamandlovu aquifer boreholes scheme to sawmills. Encompassing the feasibility studies, drilling and equipping additional boreholes | A proposal letter written to Ministry of Water with an estimated cost of USD 2 million for the detailed feasibility study |
| The rehabilitation of 15 high yielding boreholes at Rochester boreholes | Not yet done |
| Equipping the Epping Forest boreholes with an additional 20 high yielding boreholes | Not yet done |
| The design and the construction of the Insiza 800 mm steel water pipeline (Insiza pipe duplication). The design and construction of the 900 mm pipeline (32 km), pump station and reservoir (at the dam). To ensure that the pipeline operates at appropriate capacity irrespective of dam level. | Ref. Insiza Duplication Feasibility Study |
| The upgrading of the Inyankuni Pump Station | Put together with the Inyankuni – Ncema duplication proposal |
| The design and installation of booster stations along Mtshabezi pipeline in an effort to increase output | Not yet done |
| The construction of the Gwayi-Shangani project | Construction stage |
| The refurbishment of the Ncema Treatment Works | Tender stage |
| The design and construction of the Criterion-Tuli link (14,000 $m^3$). | Funds required for a detailed feasibility study. |

Source: City of Bulawayo

**Table 2.7: A snapshot of city-implemented water demand management measures since 1990**

| Land-use category | Description of Water Demand Measures Implemented | Implications of the Action |
|---|---|---|
| Citywide | Stringent water rationing<br><br>Brick-in-cistern to reduce toilet flushing water<br><br>Rising block tariff<br><br>Extensive water conservation awareness campaigns<br><br>Leak determination, repair and reduction strategies | Reduced consumption to below 60% of normal consumption levels.<br><br>Reduced leak levels from around 20,000 $m^3$/d in 2000 to about 6,000 $m^3$/d currently |
| Residential | September 2012 – simultaneous toilet flushing twice each week to keep sewer pipes from becoming blocked and damaged, considered a threat due to severe water restrictions in place (often for three days at a time). This was referred to as the big flush.<br><br>Greywater recycling in flushing toilets and gardening<br><br>Personal boreholes and rooftop rainwater harvesting | Reduced blockages in the sewer system<br><br>Reduced demand for municipal water |
| Commercial | Rainwater harvesting to supplement municipal supplies, brick-in-cistern water use reduction, intermittent water supply | Greatly reduced water consumption |
| Industrial | Borehole drilling, recycled municipal wastewater for non-potable reuse, cleaner production, rainwater harvesting to supplement municipal supplies, brick-in-cistern water use reduction, intermittent water supply | Greatly reduced water consumption |
| Institutional | Borehole drilling, rainwater harvesting to supplement municipal supplies, brick-in-cistern water use reduction, intermittent water supply | Greatly reduced water consumption |

responsible for coordinating environmental issues in the country, including climate change, through the Climate Change Management Department. Zimbabwe signed and ratified the Framework Convention in June 1992 and acceded to the Kyoto Protocol on Climate Change in June 2009. However, implementation of these agreements has been fragmented, with legislative and administrative responses contained in diverse sector policies, strategies and plans (Davis and Hirji, 2014; Dodman and Mitlin, 2015; Chivhenge *et al*., 2022).

In response to its international commitments on climate change, Zimbabwe has developed the following instruments to guide its national actions: the National Climate Change Response Strategy (2015), the National Climate Policy (2016), the Nationally Determined Contribution (2016), the National Adaptation Plan (2019), and the Third National Communication to the UNFCCC (2017). The National Climate Change Response Strategy mainstreams action on climate change in all key economic sectors (agriculture, industry, energy, mining, transport, and tourism), including for water resources, and promotes low carbon intensive pathways for economic activities. Work is continuing to ensure all sectoral policies mainstream climate change adaptation (GoZ, 2019).

The legal and governance frameworks regulating environmental protection in Zimbabwe are fragmented and sprawl over a wide range of laws and policies falling under the mandates of the ministries of environment, water and agriculture, mines and energy, health, and home affairs among others (Dodman and Mitlin, 2015; Chivhenge *et al*., 2022). The Environmental Management Act of 2002, through the Environmental Management Agency (EMA), provides the overall framework for sustainable natural resource management and environmental protection. Water is administered through the Water Act (Chapter 20: 24) and the Zimbabwe National Water Authority Act (Chapter 20: 25), both of 1998, which provide administrative and legal frameworks for the management of catchments, water abstraction

Table 2.8: SLB figures comparing non-revenue water in Harare and Bulawayo in 2016

| Performance Indicator | Harare | Bulawayo |
|---|---|---|
| Non-revenue Water (NRW), % | 60.7 | 41.2 |
| NRW, $m^3$/month | 7 766 006 | 1 571 086 |
| Cost of NRW per city per month, USD | 4 219 454 | 983 102 |
| NRW, $m^3$/h | 10 638 | 2 152 |
| Length of water reticulation in the city, km | 5 600 | 2 305 |
| Extent of NRW, $m^3$/hr.km | 0.0019 | 0.0009 |
| Extent NRW, USD/km/yr | 8 321 | 4 090 |

and regulation of water pollution. The body responsible for water administration is ZINWA, the Zimbabwe National Water Authority, which issues water permits. EMA and ZINWA are therefore critical in assisting Bulawayo's climate change adaptation efforts. The water sector is mainly guided by the Water Act and the Urban Councils Act (Chapter 29.15) of 2002 at the municipal level. A national water policy was developed in 2013, and it highlights the need to include the impact of climate change in all water-related planning. Proposals from the Water Policy, which are still to be implemented, include the establishment of a water sector regulator, the ring-fencing of water accounts, and the separation of water supply functions into those of the water services authority and the water service provider. These implementation gaps are mainly a result of capacity limitations in institutions, finances, and social and technical as well as human resources (Tom and Munemo, 2015; Taonameso *et al.*, 2022). A national water resources master plan for 2020–2040 is in the process of being developed by the Government with support from the World Bank. It will serve as the blueprint for sustainable water resource development, utilization, and management in the country.

Bulawayo City Council purchases raw water from ZINWA, treats it, and distributes it within the council area and to some outside bulk consumers. It is empowered by the Urban Councils Act to propose cost-recovery tariffs and seek approval from the central Government. Stakeholders participate in annual budget consultations and thus have a say on the levels of water tariffs. In the absence of a water sector regulator, urban local authorities embarked on a service level benchmarking project based on a peer review system. This project was funded by the World Bank and ran from 2012 to 2019, when it was stopped by the central Government.

### 2.3.4 Technology

Through various projects and studies, Bulawayo has managed to map and model its water supply system in a GIS environment and has controlled water losses through pressure management. The council has explored the introduction of prepaid water meters to improve revenue collection and manage demand but it shelved the idea because of customer resistance. Water demand management could play a crucial role in extending the available resources for a few years, but the need to develop additional water supply infrastructure remains critical. Distribution losses could be reduced from the current high levels of about 45 per cent to about 20 per cent through pipe lining, pipe replacement, and detection of illegal connections, resulting in a saving of about 31,000 $m^3$/d. This is likely to be a cost-ffective action over the short term compared to developing new water sources. The Epping Forest groundwater source could provide an additional 10,000 $m^3$/d of raw water in the short-to-medium term.

A study by Norplan (2001) on water loss reduction strategies in Bulawayo established the acceptable background losses in the city's distribution system at 100 litres per hour per kilometre of mains. Background losses are the aggregation of small individual leaks and overflows that are too small to seek out and repair economically. The unit value for background installation losses (plumbing) was found to be 1.5 L/h

**Table 2.9: Cost systems for Bulawayo water based on 2012–2017 SLB data**

| Item Description | Unit | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|
| Regular Staff and administration | USD | 253 982.03 | 67 300.00 | 4 102 604.00 | 4 082 911.52 | 2 126 699.39 | 4 237 721.00 |
| Outsourced/Contract Staff Costs | USD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Electricity Charges/ Fuel Costs | USD | 789 178.00 | 785 079.00 | 9 356 512.00 | 8 779 484.40 | 9 691 778.57 | 9 972 864.00 |
| Chemical Costs | USD | 261 983.00 | 435 754.00 | 197 360.00 | 209 602.18 | 276 174.80 | 1 712 232.00 |
| Repairs/Maintenance Costs | USD | 201 370.00 | 151 801.00 | 2 010 550.00 | 1 049 788.90 | 1 530 169.00 | 2 144 135.00 |
| Bulk (Raw/Treated) Water Charges | USD | 25 200.00 | 0.00 | 812 186.00 | 1 861 033.50 | 1 674 604.88 | 1 027 297.00 |
| Other Costs | USD | 4 550.00 | 0.00 | 360 967.00 | 2 578 036.50 | 1 735 888.38 | 549 265.00 |
| **Total Operating Expenditure** | **USD** | **1 536 263.03** | **1 439 934.00** | **16 840 179.00** | **18 560 857.00** | **17 035 315.00** | **19 643 514.00** |
| | | | | | | | |
| Water produced and supplied to the distribution system | $m^3$/yr | 42 885 096 | 40 635 676 | 43 005 347 | 45 610 440 | 44 569 298 | 45 737 433 |
| Production cost per $m^3$ of water | USD | 0.04 | 0.04 | 0.39 | 0.41 | 0.38 | o.43 |
| | | | | | | | |
| Average water tariff | USD | 0.73 | 0.82 | 0.72 | 0.63 | 0.53 | 0.48 |
| Cost recovery (Benchmark is 150%) | % | 194.2 | 200.0 | 184 | 155.8 | 144.0 | 111.3 |
| Bill collection efficiency (Benchmark is 90%) | % | 60.2 | 76.2 | 63.3 | 28.3 | 30.0 | 27.9 |

per house. These values are used to establish target levels for minimum night flows (MNF) in the different district metering zones. MNF is the measured flow into a controlled district metered area (DMA) of a network during the period of minimum demand; that is, between 1 a.m. and 4 a.m. It is estimated that the water reticulation network in Bulawayo is about 2,381 km, so the background losses are roughly 6,000 $m^3$/d out of the 52,000 $m^3$/d lost in 2017. Norplan (2001) estimated the economic level of leakage at 6,800 $m^3$/d, which was 7 per cent of the March 2000 demand. The background losses from the distribution system should be reassessed after MNF has been measured in all the metering zones. Table 2.8 shows that Bulawayo was doing comparatively well on non-revenue water in 2016 because of commitments to control water losses over the years, although its situation remains unsustainable.

### 2.3.5 Financial sustainability of Bulawayo water supply

The average production cost of water in Bulawayo is about USD 0.40/$m^3$ and the average water tariff is about USD 0.50/$m^3$, based on 2012–2017 SLB data (see table 2.9). The council was just managing to break even on the water supply account. The coming on board of the Gwayi-Shangani Dam water at an estimated capital cost of USD 1.5 billion and the Epping Forest boreholes at USD 5.2 million will greatly increase the water cost, especially considering ZINWA's blended pricing system and the numerous dam projects in which they are currently involved. ZINWA will be selling water from these projects to Bulawayo City Council. The council might need to increase its tariffs and cost-recovery rates progressively to build reserves and avoid sudden increases in tariff levels when the Gwayi-Shangani water project is completed.

Experiences from Cape Town, South Africa, show that charging punitive tariffs for high water consumers in an increasing block tariff system would help reduce demand, encourage adaptive behaviours, and boost revenues for BCC and ZINWA (Simpson *et al*., 2019; Ouweneel *et al*., 2020). Improving revenue collection through the use of information communication technologies such as smart billing and metering would also help provide operating funds for BCC, as currently water revenue collection has gone down to unsustainable levels (see table 2.9). The BCC is the only council that provides free basic water in Zimbabwe and it still manages to balance its books (if only it could improve its bill collection efficiency). The monthly water tariff bands in 2021 were as follows: 0–5 $m^3$ – USD 0.00; 5–14 $m^3$ – USD 0.57; 14–25 $m^3$ – USD 0.77; 25–27 $m^3$ – USD 1.15; and above 27 $m^3$ – USD 1.84. BCC's recent decision to ring-fence its water revenue, based on a directive from the Ministry of Local Government, will improve its financial resources. Water pricing should reflect water's true cost (Girardin, 2019). This will not only improve water use efficiency by encouraging conservation and recycling, but will also provide the funds for ZINWA and local authorities to carry out important rehabilitation and climate-related initiatives. Establishing a national water regulator would help remove water pricing from political influence, set prices at levels where costs can be met, and provide better certainty to water consumers and urban water management authorities such as BCC (Grafton et al., 2020). Also, an informal water market, as is the case in Lusaka, could be investigated as a mechanism to promote more flexible and efficient use of water (Keener *et al*., 2010).

## 2.4. IMPACTS AND CONSTRAINTS

#### Impact of interventions

The various consumer categories seem to have reacted differently to the persistent water situation in Bulawayo in these ways (Norplan, 2001; Bosch Stemele, 2012; VisionRI, 2019):

- The per capita consumption in all areas has remained substantially constant for a long time. There are marginal reductions during water rationing periods, but the total consumption returns to a similar overall amount in non-rationing periods.
- Bulawayo's water consumption levels have been determined by availability, not demand, for a prolonged period. The use of restrictions, rationing, and penalties has drastically reduced consumption. The residents of Bulawayo have adjusted to the situation of scarce water resources so that even when restrictions were lifted, consumption has not returned to its former level.
- Average number of pipe bursts per 100 km in a month is low at 5.0 compared with the capital city, Harare, which had 13.1 in the 2012–2016 period. This is due to better infrastructure management induced by water scarcity.

**Constraints**

Several studies conducted in Zimbabwe revealed some constraints and gaps related to financial, technical, and capacity needs (Davis and Hirji, 2014; Brazier, 2015; Maviza and Ahmed, 2021). The level of awareness of climate change in Zimbabwe remains low (Mudombi *et al*., 2014; Evans, 2015). This limited awareness negatively affects climate change reporting and the implementation of related initiatives. The inadequacy and inconsistency of data can be attributed mainly to the limited capacity (technical and financial) of key institutions to record or collect data. Loss of engineering design data from previous initiatives is also a challenge that needs to be overcome. Some of the equipment used to make observations has since reached the end of its useful lifespan, making it obsolete and thus compromising data quality and availability. The sharing and use of data by Government agencies is limited by a "silo mentality", whereby agencies are reluctant to release their data for free or sell at unreasonable prices. Climate data from the Meteorological Services Department is particularly inaccessible as it is sold at exorbitant rates. This kind of data is rarely used for personal purposes. One possible solution to the technological challenges is for local institutions and international technology developers to partner in producing and using appropriate technologies.

## 2.5. OUTSTANDING ISSUES

To supply Bulawayo and surrounding irrigation schemes with water sustainably, the following actions are required:

i. A climate adaptation plan for the city should be developed, linked to the current draft city masterplan.

ii. Water tariffs need to be shielded from political interference and, instead, be based on scrutiny from a professional regulator. Prepaid smart water meters, with sufficient guarantees for lifeline support to the poor and vulnerable, are a long-term solution to efficient bill collection challenges. However, NRW has to be reduced first to sustainable levels of around 20 per cent and constant water supply restored so that consumers have confidence in the whole system. The South African city of Durban, which has a twinning relationship with BCC, is a good example to follow.

iii. Important lessons on recycling for potable reuse can also be learned from Windhoek.

iv. Maintaining updated network data and continuing to improve leakage response and customer response times is needed.

v. Carrying out periodic water audits for the whole city and in district metering zones should be maintained.

## 2.6. CONCLUSION AND WAY FORWARD (LESSONS LEARNED)

The case study of climate change impacts on water supplies in Bulawayo offers important lessons to local and regional cities on how to cope with less water through committed water demand management and sustained infrastructure development. The city has successfully managed to inculcate a sense of personal water stewardship to the extent that water-use patterns rarely change even in high rainfall seasons when water rationing measures are lifted. The commissioning of the Gwayi-Shangani Dam, expected in 2023, is going to open an irrigation corridor along the pipeline route and offset the high costs of the project for the city and the Government. The fact that the Government also funded this project at the national level is good in terms of sharing the burden and allowing the regional economy to grow. On the negative side, the resilience and sustainability of Bulawayo City Council are threatened by high water losses and poor bill collection. Bulawayo needs to network with regional cities to share its successes and learn other best practices.

CHAPTER 3

# Water supply challenges in Gaborone city a response to changing climate and rapid urbanization

A case study of Gaborone by Odirile P.T[2]., Moalafhi D.B[3]., and Kalabamu, F.T[4]

## 3.1. INTRODUCTION

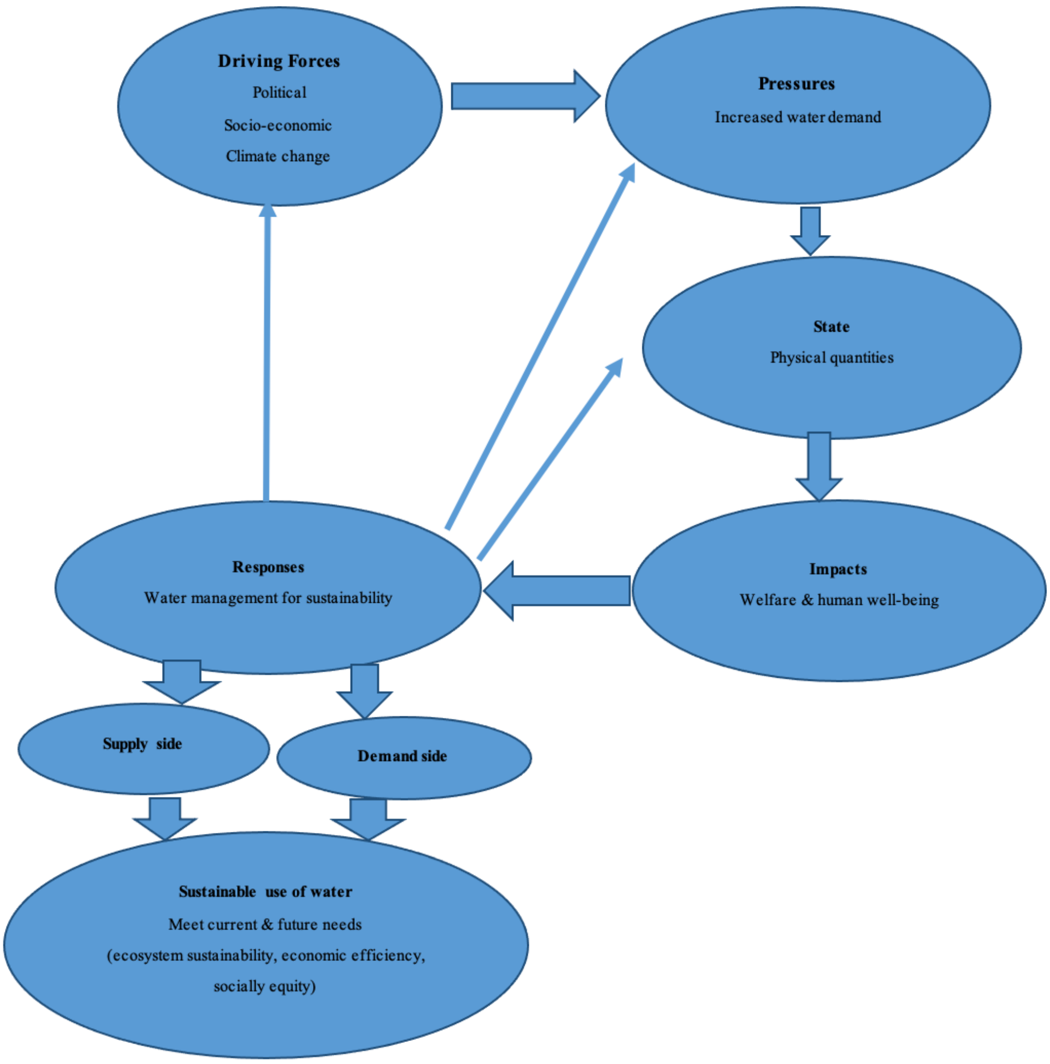
This chapter seeks to (a) explore water supply problems in the city of Gaborone; and (b) assess the effectiveness and sustainability of solutions applied to meet increasing water demands in the city in light of climate change and rapid urbanization processes being experienced in the Eastern and Southern Africa regions. The chapter is based largely on published resources and data obtained from the Water Utilities Corporation, the Department of Water and Sanitation in the Ministry of Land Management, Water and Sanitation Services, and the Department of Meteorological Services in the Ministry of Environment, Natural Resources Conservation, and Tourism. We note that while water demand in Gaborone has been influenced by numerous factors, including the city's spatial expansion, rapid population growth, and increasing affluence, water supply initiatives have been constrained by the country's hydrological conditions, declining rainfall, increasing temperatures, and evaporation. The country has overcome these constraints by initially importing water from neighbouring South Africa and, later, transferring water from dams built up to 400 km from Gaborone.

This chapter is organized as follows: after this introduction is a short description of the conceptual framework and a brief narrative on hydrology, rainfall, climate change, and urbanization processes in Southern Africa and Botswana in particular. The narrative provides a context or framework for viewing and understanding the water supply challenges faced by the city of Gaborone. The bulk of the chapter focuses on Gaborone's population growth and physical expansion as well as declining rainfall amid increasing temperatures and their implications on the water demand-supply equation. The last sections discuss the city's water supply sources, interventions and actions undertaken to meet the city's ever increasing water demand.

### 3.1.1. Conceptual framework

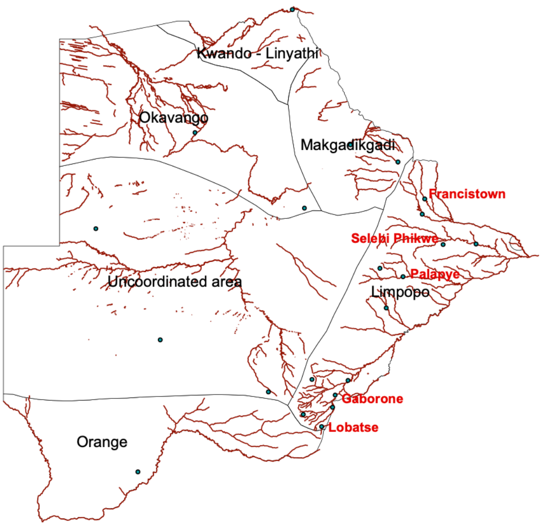
Sustainability of water sources supplying Gaborone can better be appreciated within the modified Drive-Pressures-States-Impacts-Responses(DPSIR)framework as adopted from Ker Rault et al., (2004) and Koundouri et al., (2016) (see figure 3.1). This internationally recognized framework enables analysis of the important and interlinked relationship between social and environmental factors. Regulation of water and related transactions lies with the Botswana Government. This entails the development, mobilization and management of water resources for socio-economic advancement. This, coupled with climate change and within the context of increasing population growth and per capita water consumption, often puts pressure on the already limited water resources as demand increases despite declining resources. This affects welfare and human well-being. Intervention measures towards optimization of water resources cover the demand (metering, public education campaigns, and appropriate water pricing that is socially acceptable to reduce wastage and generate revenue to maintain infrastructure) and the supply sides (new water sources, leakage management and water reuse, for example). This gives the framework for sustainability of current and future water resources within the context of the three strategic objectives of Integrated Water Resources Management (IWRM), ecosystem sustainability, and economic efficiency and social equity.

Figure 3.1: Water management for sustainability: DPSIR framework




Souce: Ker Rault et al., 2004; and Koundouri et al., 2016).

Figure 3.2: Main drainage basins of Botswana showing rivers and main towns that are major demand centres over the east




Source: Authors

## 3.1.2. Regional and national contexts

### 3.1.2.1. Hydrology

Gaborone lies within the Limpopo River basin, which has its headwaters in the vicinity of Johannesburg, South Africa. Many of the river's main tributaries drain into South Africa's northern Transvaal. The river basin covers an area of approximately 412,938 km$^2$, falling within four countries: Botswana, Mozambique, South Africa and Zimbabwe. The basin has a diverse water use in which its middle to lower parts are dominated by agriculture while the upper parts are dominated by urban, industrial and mining water use sectors (Moalafhi et al., 2017). The major urban centres and industrial activities of the countries making up the basin are situated either within the vicinity of the headwaters or are dependent on the basin's water resources. Despite this, recurrent droughts adversely affect the socio-economic activities of the resident population. Since rainfall is low, highly variable, and generally declining over time, the little available water is mostly depleted by evaporation. All these factors make water availability an ever-present challenge.

As per capita water consumption increases, resulting from an increasing population and other high water consumption socio-economic activities across the basin, abstraction rates over most of the sub-basins are becoming unsustainably high (Moalafhi et al., 2017).

As shown in figure 3.2, all main river systems in Botswana originate from outside the country. The ones originating in Botswana are ephemeral and carry limited water supply. With a semi-arid climate, Botswana experiences generally low and highly variable rainfall (Parida and Moalafhi, 2008a). Rainfall is concentrated in the period October-April, and most rivers are seasonal or ephemeral. This temporal variability of rainfall is mirrored in the time distribution of run-off and river flow. Generally, variability is higher where rainfall is lower. Within the context of the changing climate, rainfall variability is projected to increase in future. There is also a high variation in rainfall from one area to another. Even over the same catchment area rainfall can vary highly from one part to another. This problem is further compounded by flat topography, which adversely affects the feasibility, location, size and types of surface water storage (Parida and Moalafhi, 2008b).

### 3.1.2.2. Climate change in Botswana and Southern Africa

Projections over Southern Africa have revealed increasing temperature and declining precipitation over Botswana. Maúre et al. (2018) assessed projected temperature and precipitation over Southern African under 1.5$^0$C and 2$^0$C of global warming levels (GWLs) as simulated by 25 CORDEX regional climate models under the Representative Concentration Pathway 8.5. From their findings, temperatures are projected to increase, generally, by 2$^0$C and 2.5$^0$C by 2100 over Southern Africa using the 1.5$^0$C and 2$^0$C GWLs, respectively. On the other hand, precipitation is projected to increase by 0.1 mm/day using the 1.5$^0$C GWL and decrease by 0.2 mm/day using the 2$^0$C GWL by 2100. The uncertainty of these projections is modulated by taking averages from the ensemble of individual models used. These results align with a slight increase in precipitation over Gaborone using station rainfall from 1990 to 2019. With the projected decreases in precipitation, especially using the most likely 2$^0$C GWL, the study of Maúre et al. (2018) paints a bleak future for the major river basins of Southern Africa (Limpopo and Zambezi). The study suggests the result of decreased precipitation will likely result in reduced water recharge and increased rainfall uncertainty for these shared resources. Botswana's capital, Gaborone, is within the Limpopo River basin. Development of alternative forms of energy from hydropower, livelihoods and appropriate policy interventions is critical for future sustainability of these shared water resources. These findings were also supported by Nkemelang et al. (2018) when analysing projected changes in temperature and precipitation extremes at 1.0$^0$C, 1.5$^0$C and 2.0$^0$C warming over Botswana. The study revealed a progressive drying across Botswana, along with increased heavy precipitation events, reduced wet spell events, and increased dry spells. With the rise in temperature the atmospheric capacity to hold moisture increases. This means that moisture accumulates in large quantities before it rains. Once it rains, these large quantities result in high-intensity rainfall, leading to flooding over short periods. Since it takes longer to accumlate moisture this results in the frequency of extended dry spells between rainfall events. Water resources are more likely to be heavily impacted by the reduced total precipitation, increased intensity and longer dry spells, and greater evaporation under more extreme temperatures.

### 3.1.2.3. Botswana climate and rainfall variability

The semi-aridity of Botswana's climate is typical of Southern Africa. The regional climate is influenced by the size and shape of the southernmost finger-like tip of the African continent and its latitude (Thomas and Shaw, 1991; Tyson and Crimp, 2000; Parida and Moalafhi, 2008a, b).

Rainfall across the country is highly variable and limited. Batisani and Yarnal (2010) investigated rainfall variability trends for 1975–2005, in which they found that rainfall was generally decreasing significantly, owing to decreases in the number of days with rainfall. Another study by Moalafhi et al. (2012) projected precipitation and temperature up to 2050. These predictions show precipitation will decrease by 5 per cent, while temperature will increase by 2.5°C. The likely impacts will be further 7.9 per cent of decrease in precipitation and 4.4 per cent reduction in river flows across the whole of Botswana. Rainfall is the main recharge factor for surface and groundwater resources, and its decline, in the face of increasing water demand, is worrisome. Despite insignificant decreases in rainfall, this could be significant in the future and have implications for surface and groundwater recharge. Increasing temperature also implies increased evaporation (which is estimated at 2,000 mm per annum), especially in Botswana's shallow surface water storages. Thus this will also compromise the water security of the country at large. Water shortages in the country are also worsened by the effects of climate variability, such as the 2015–2016 El-Niño. In July 2015, Botswana declared a drought emergency following a second year of poor or failed rains across most parts of the country. Figure 3.3 shows the drought severity map of Botswana, indicating the western part of the country is more severely affected than the east. The 2015–2016 drought was rated extremely severe and the worst in the last 34 years by Department of Meteorological Services (World Bank Report, 2017).

Figure 3.4: Botswana Drought Severity Map (2014/15)

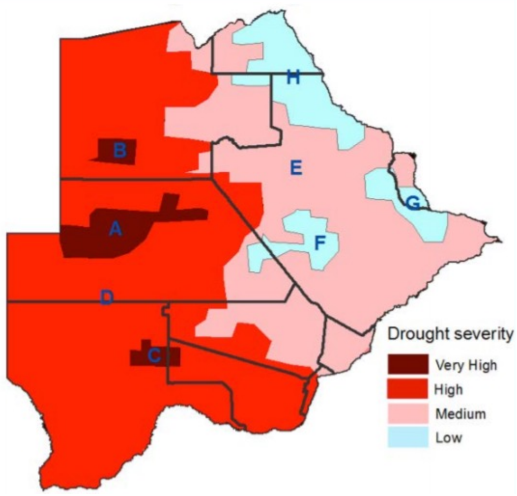
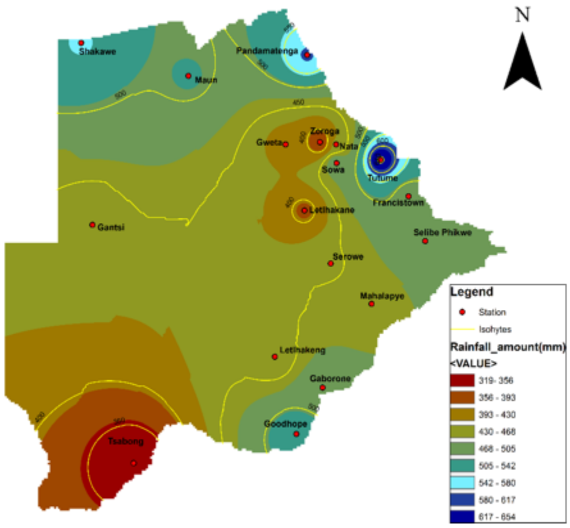



Figure 3.3: Botswana Annual Precipitation Map




Source: DMS (2015)

Annual rainfall shows a decreasing gradient from about 600 mm/year around the north to 250 mm/year towards the south-westernmost parts of the country (figure 3.4). Temperatures are usually high, resulting in accelerated loss of water from surface water storages. Since Botswana's terrain is mostly flat and dam sites are limited, surface water storages are very shallow, resulting in high evaporation rates. All these translate into limited recharge of surface and groundwater resources. Botswana's reservoirs have disproportionately large surface areas as compared to depth due to the flat topography. This results in high unit costs of water in Botswana (Parida and Moalafhi, 2008a).

### 3.1.2.4. Population growth and urbanization in Botswana

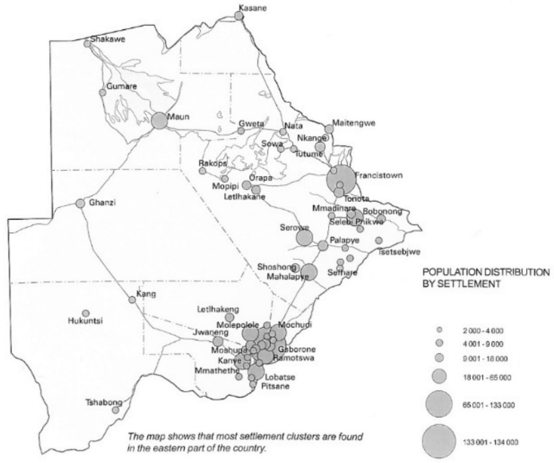
Pre-independence census, taken in 1964, put Botswana's population at 514,876 inhabitants. It was 1.4 million by 1991; and at 2 million by 2011 (Kalabamu and Morolong [2004: 69] and Statistics Botswana [2020:12–14]). Today's population of 2.4 million is expected to reach around 3.7 million by 2050 (Nyoni, 2019). This means the Government will need to make additional investments to sustain or improve on current water supply levels.

At independence from the United Kingdom in 1966, Botswana was largely a rural population. Only 4 per cent of the national population lived in towns. The proportion and number of people living in urban areas increased to 9.8 per cent by 1971 and then to 62.0 per cent in 2011 (Kalabamu and Morolong, 2004; and Statistics Botswana, 2014).

An urban area is locally defined as any village or town of at least 5,000 inhabitants of whom at least 75 per cent of its workforce is engaged in non-agricultural activities. Botswana's urbanization has been a constant feature of its development since independence in 1966 (MLH, 2014). Due to the conversion of rural villages into urban settlements, rural-urban urbanization is the main factor in the distribution of the country's population. The migration of rural populations is dominated by people looking for employment. Most of the developments occur in the Greater Gaborone cluster, hence the greatest concentration of people is in this area as shown in figure 3.5. This situation makes Gaborone the country's focal commercial and educational centre, and it is no wonder it constitutes the main cluster (see figures 3.5 and 3.6). With the ongoing economic activities and population influx to urban centres, and the natural population growth with associated shift to non-agricultural activities, there has been an expansion in housing, road and industrial units, among others (Moalafhi, 2004; BIWRM-WEP, 2013).

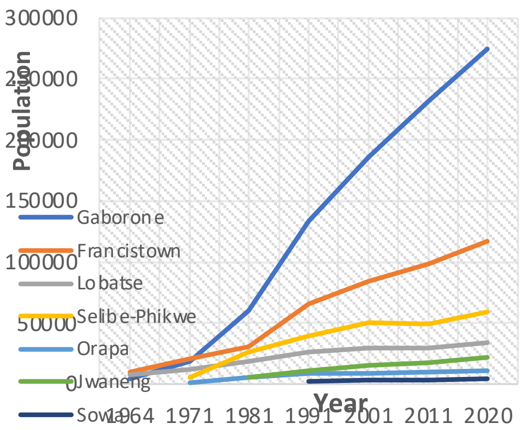
The increase in the number of townships and reclassified villages has inevitably increased the proportion and number of people living in urban areas, from 9.8 per cent in 1971 to 62.0 per cent in 2011 (Kalabamu and Morolong, 2004). Although, according to UN-Habitat (2016), urbanization stimulates economic growth and human development, it also requires improved infrastructure facilities including adequate potable water and sanitation.

Figure 3.5: Population distribution by settlement as per 2001 census




Source: Government of Botswana, 2000:7

Figure 3.6: Population growth for Gaborone, other cities in Botswana (1964–2020)




Source: Statistics Botswana 2014 and 2020

Note: Population for 2020 are estimates.

### 3.1.2.5. Water demand and supply in Botswana - An overview

Botswana faces a major challenge of water scarcity due to its limited water resources. Most of the surface water sources originating in the country have been exploited. The country's four major river systems—namely the Okavango, Kwando-Linyanti-Chobe, Limpopo and Molopo—are transboundary.

Botswana's dams have disproportionately large surface and catchment areas compared to annual yields storages. However, high rainfall intensities are common resulting in significant inflows of water and sediments into surface water storages. Also, these high-intensity rainfalls are becoming more frequent, with increased dry spells in between. Rain-fed floods are causing more damage to property and farms. Moreover, the floods do little to replenish surface water amidst high temperatures and evaporation rates of 2 metres per year, which results in reduced reservoir storage.

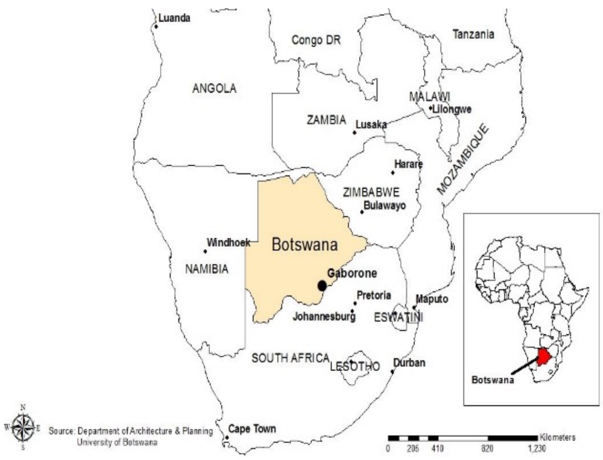
According to the Botswana National Water Master Plan Review of 2006, water demand across the whole country is expected to increase by 46 per cent from 232.9 mm$^3$ in 2016 (with a population of 2.16 million) to 339.7 mm$^3$ per annum in 2035 (with a projected population of 3 million) due to economic and population growth and improved living standards (Botswana Government, 2006).

### 3.2. GABORONE: STUDY AREA

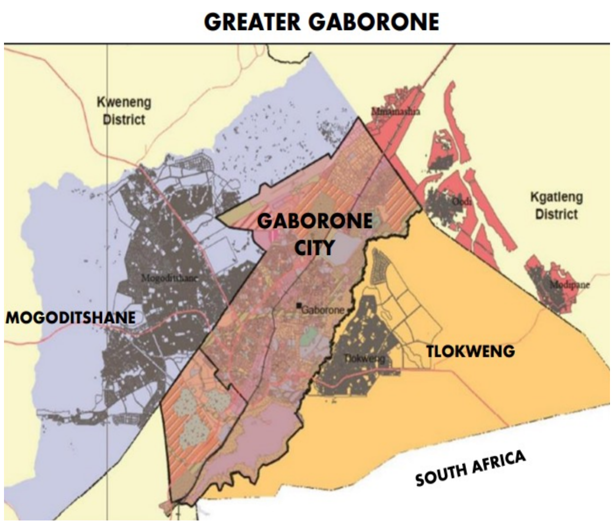
Gaborone, the study area, lies in the country's east, close to the South African border, as shown in figure 3.7a. The city is on Government-owned land surrounded by two villages, Tlokweng to the east and Mogoditshane to the west, and freehold farms on the north and south (see figure 3.7b). The decision to make Gaborone a town and the national capital was taken in 1962, four years before independence from Britain. Besides serving as the national capital, Gaborone is the country's administrative, commercial, industrial, transport and financial centre. The city also serves as the main transport and communications hub for Botswana and neighbouring countries. Gaborone is also the headquarters of all banking and financial institutions and major industries, besides meat processing and resource-based industries such as brick factories.

Despite having been selected as a site for the capital because of its adequate water resources, Gaborone experiences enormous water demand and supply challenges arising from the country's rapid population and urbanization growth and several ecological and environmental issues. The challenges have been exacerbated of lateby climate change and vulnerability.

Figure 3.7: (a) Location of Gaborone in Southern Africa; (b) Surrounding villages




(a)




(b)

Source: Authors

### 3.2.1 Population growth in Greater Gaborone

As indicated in table 3.1, Gaborone's population increased rapidly between 1964 and 2001. In contrast, villages surrounding the city (namely, Tlokweng, Mogoditshane and Gabane) were initially losing inhabitants, but some (notably Mogoditshane) started to grow rapidly after 1971. Rapid population growth in Gaborone and surrounding settlements has for decades skewed the national demand for water towards the country's south-east.

**Table 3.1: Population of villages around Gaborone (1964–2011)**

| Year | 1964 | 1971 | 1981 | 1991 | 2001 | 2011 |
|---|---|---|---|---|---|---|
| Gaborone | 3 855 | 18 799 | 59 657 | 133 468 | 185 891 | 231 592 |
| Tlokweng | 3 711 | 3 906 | 6 657 | 12 501 | 21 133 | 37 364 |
| Mogoditshane | 2 548 | 1 075 | 3 125 | 14 246 | 32 843 | 58 632 |
| Gabane | 5 402 | 1 936 | 2 688 | 5 975 | 10 399 | 16 671 |
| Mmopane | na | 539 | 584 | 1 249 | 3 512 | 17 845 |
| Metsimotlhabe | na | 50 | 395 | 1 586 | 4 997 | 9 270 |
| Greater Gaborone | 15 516 | 26 305 | 73 106 | 169 025 | 258 775 | 371 374 |

Source: Kalabamu and Morolong, 2004 and Statistics Botswana, 2014

### 3.2.2 Spatial growth in Greater Gaborone

Old and new settlements in Greater Gaborone have expanded spatially quite rapidly with their respective population increases. At the time Gaborone was designated as the country's capital it consisted of three clusters: the camp, which had developed into a residential suburb; the town, which had been built east of the railway station; and an unplanned (squatter) settlement, named Naledi (meaning star) that had emerged on a piece of Government land zoned for industrial use. The three clusters have merged into one township and sprawled northwards and westwards. The villages of Tlokweng, Mogoditshane, Gabane and Mmopane have also expanded in various directions and merged with Gaborone (see figure 3.7b).

Gaborone's spatial expansion (like all towns and cities in Botswana) has been controlled and guided by urban development and land-use plans prepared by the Government. The first Gaborone Master Plan was drawn up in 1963 while the latest was approved in 2009. These plans seek, inter alia, to ensure the city grows in an orderly manner and is provided with adequate infrastructure services. The plans are strictly enforced. Consequently, the Government has maintained Gaborone as a city with relatively well-planned, orderly and serviced residential suburbs. Despite this, the city and its abutting settlements have been expanding at very low densities characterized by large plots, single-storey buildings and detached houses. This development has resulted in the loss of agricultural land, long travel distances to work, schools, malls, and unsustainable utility costs, including water supply and reticulation.

### 3.2.3. Unplanned settlements

Old Naledi, the first and the only substantive unplanned (squatter) settlement within Gaborone, is as old as the city. Old Naledi emerged in the early 1960s as a spontaneous camp for labourers in the city's construction industry. By 1971, Old Naledi had 4,075 residents and covered an area of approximately 42 hectares (Kalabamu and Morolong, 2004: 116). As a spontaneous settlement, Old Naledi lacked health, education, recreational and other community facilities and basic infrastructure services such as roads, electricity, sanitation and water. The Government tried to remove the occupants to an adjacent planned area (nicknamed New Naledi), but they resisted and remained or returned to Old Naledi (Van Nostrand, 1982). Then, the Government decided to retain and upgrade the illegal settlement. Through the upgrading effort (1978 to 1981), the Government granted land rights and provided essential services including gravel roads, pit latrines and communal water taps. However, the use of pit latrines in overcrowded areas such as Old Naledi was considered a health hazard. The latrines could easily pollute underground water, the nearby Notwane River and Gaborone Dam. Consequently, the latrines were replaced with central sewerage systems. The communal water supply system has been replaced with private water connections.

Figure 3.8: Monthly total rainfall for Gaborone over past three decades showing a decline

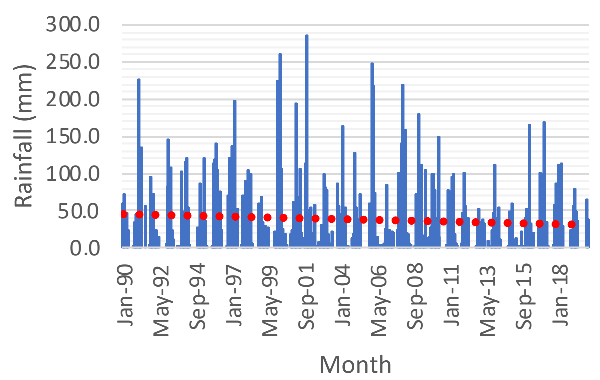
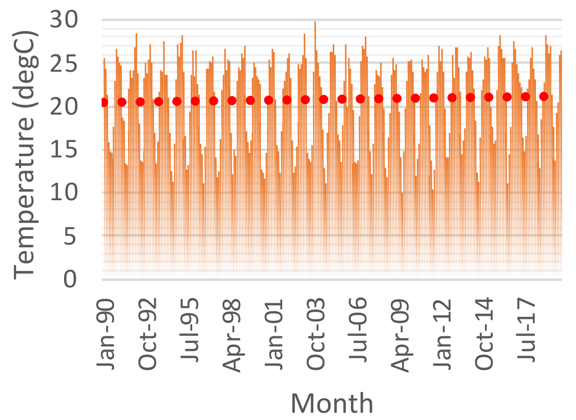



Figure 3.9: Monthly average temperature for Gaborone over past three decades showing an incline




At present Gaborone does not have any illegal or informal settlements. This is largely due to Government's adherence and enforcement of town planning laws, building regulations and support programmes. New residential, commercial and industrial areas are planned under the Accelerated Land Servicing Programme and Public-Private Sector Partnership (PPP) initiatives. These areas are planned and serviced with fundamental infrastructure (including water, sewerage and roads) before the land is allocated or sold to individuals, companies or institutions for development. However, some posh residential developments on privately owned freehold land (for example, in Gaborone North) have tended to proceed in an unsatisfactory manner – without reticulated water, sewerage, tarred roads and streetlights. Due to the private nature of the property, there is no legislation regulating the administration and development of freehold land unless it falls within a statutory planning area. Residents in these posh suburbs rely on private boreholes and water bowsers.

### 3.2.4. Climate variability, climate change and water availability

Currently, Gaborone is experiencing declining rainfall and increasing temperature. These are  key climatic variables with implications for water resources. Looking at the three decades from January 1990 to December 2019, monthly rainfall over Gaborone had been decreasing (see figure 3.8), although insignificantly. Over the same period, the temperature has also been decreasing, albeit insignificantly (see figure 3.9). The mean annual rainfall varies from a maximum of over 650 mm/year in the north-eastern area of Chobe District to a minimum of less than 250 mm/year in the extreme south-western part of Kgalagadi District as shown in figure 10 (DWS, 2018). Gaborone's annual rainfall averages 600 mm/year with a coefficient of variability (CV) of 40 per cent (Byakatonda et al., 2018).

### 3.2.5. Water demand pattens in Gaborone

Figure 3.10 shows that there has been a steady increase in the total per capita water consumption for Gaborone, which exceeds that at other locations within the city's greater area. This level of consumption is projected to increase into the future. Figure 3.11 gives projected water demand disaggregated into domestic, institutional and commercial for Gaborone. The projections show that total water demand for Greater Gaborone will increase steadily between the years 2001 and 2023; from 44.8 (year 2013) to 82.4 $Mm^3$/year (year 2035). However, indications are that the institutional demand is the greatest contributor to this total demand increase, with domestic water requirements falling after 2009 and it is estimated that it will be lowest in 2035. The water demand for Greater Gaborone constitutes 62 per cent of the total demand in the North-South Carrier (NSC) pipeline. As expected, water demand estimates for Gaborone exceed those of other major towns as shown in figure 3.12. Domestic, Government, commercial and industrial water usage constitutes about 34 per cent, 47 per cent and 19 per cent of Gaborone's total water consumption, respectively (World Bank, 2014). Efforts toward phasing out of public standpipes have not significantly curtailed water wastage, since the poor among the communities should not be denied access to affordable or free water. With many public standpipes converted to pre-paid, quantities of water accessed through public standpipes have more or less remained the same (see figure 3.13).

Figure 3.10: Greater Gaborone per capita water consumption

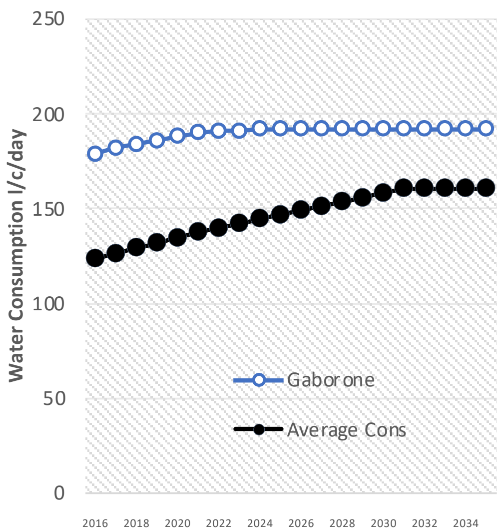



Figure 3.11: Variations in water demand trends in Gaborone 2001 to 2035

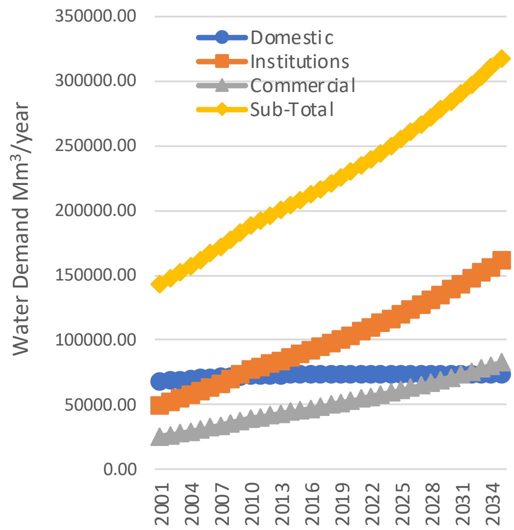



Figure 3.12: Comparison of water demand estimates with other major towns

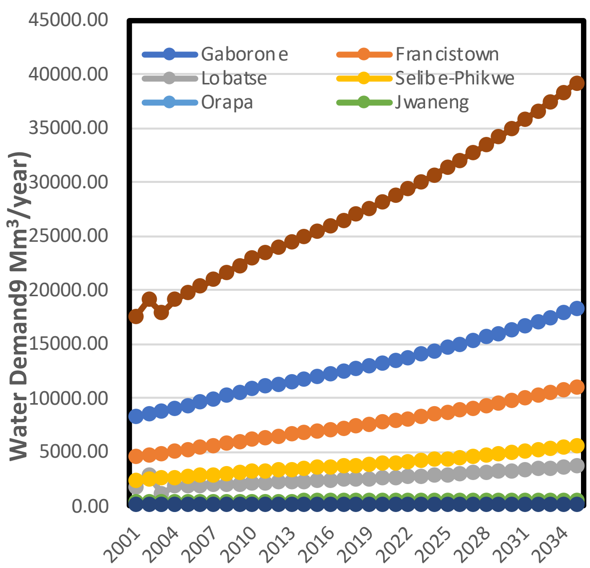
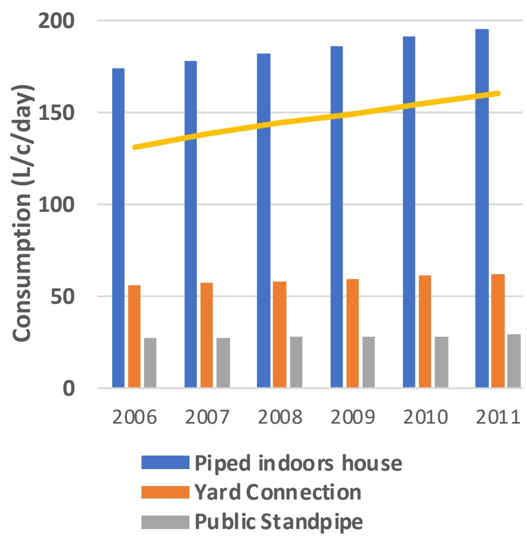



Figure 13: Comparison of water upply patterns to household, yard and public standpipes in Greater Gaborone




As a result of the foregoing, water shortage is an ever-present challenge. Gaborone is the main population cluster with all pull factors of modernity more than any other location in the country. With generally declining rainfall and increasing temperature, water resources that supply the city and its immediate environs are challenged. This, with increasing natural population growth and migration to the area and increased per-capita consumption, means challenges to water supply to the city will worsen into the future.

**Table 3.2: Characteristics of dams supplying water to Greater Gaborone**

| Classification | Supply Dams | | | | | |
|---|---|---|---|---|---|---|
| | Molatedi | Gaborone | Bokaa | Letsibogo | Dikgatlhong | Shashe |
| Distance from Gaborone (Km) | 96.8 | 10.5 | 29.3 | 411.0 | 457.0 | 412.0 |
| Catchment Area ($Km^2$) | 8 422 | 4 300 | 3 570 | 5 693 | 7 810 | 1 700 |
| Surface Area ($Km^2$) | 36 | 15.0 | 7.0 | 16.0 | 45.0 | 15.6 |
| Dam Depth (m) | 29.0 | 22.0 | 8.0 | 20.0 | 41.0 | 20.0 |
| Full Supply Capacity ($Mm^3$) | 201.0 | 141.4 | 18.5 | 100.0 | 400.0 | 85.0 |
| Full Supply Level (FSL) (m) | 958.0 | 998.0 | 954.0 | 848.0 | 875.0 | 971.5 |
| Minimum Operational Storage % of Max Storage | - | 15.0 | 3.0 | 5.0 | 4.0 | 15.0 |
| surface area to volume ratio | 0.034 | 0.045 | 0.125 | 0.50 | 0.024 | 0.050 |
| Annual Average Inflows ($Mm^3$/year) | - | 33.26 | 9.62 | 56.86 | 114.75 | 79.28 |
| Evaporation ($Mm^3$/year) | - | 38 | 13 | 35 | | |
| Sustainable Yields ($Mm^3$) | - | 10 | 1.1 | 20 | | |
| Year Constructed | 1987 | 1966 | 1993 | 1997 | 2012 | 1970 |
| % Contribution to Greater Gaborone* | • 16 at full allocation<br>• 8 at Half allocation | 56 | 25 | 36 | + | + |

* Source: Statistics Botswana (2012);
+ Dams to be connected in the future
- Information not available

### 3.2.6. Water supply sources for Gaborone

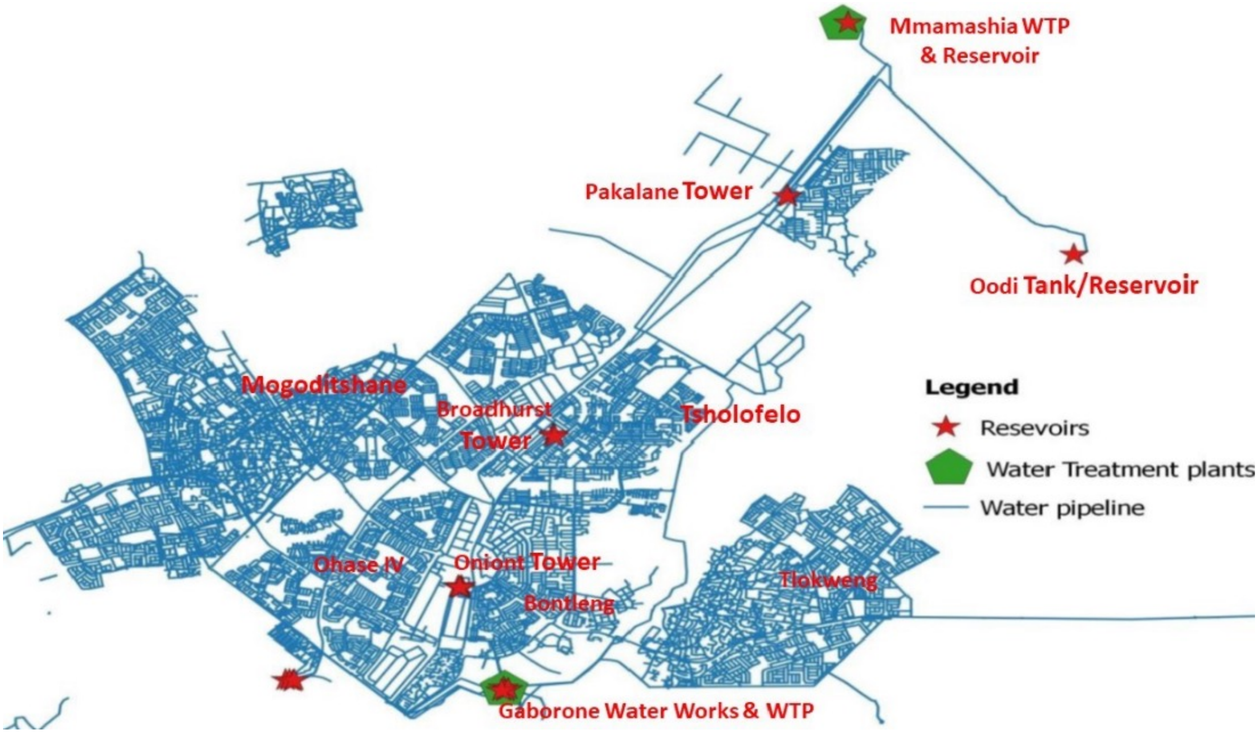
Gaborone's main water sources are the dam, by the same name, within the city; the Bokaa Dam, some 40 km to the north-east; and the Molatedi Dam in South Africa. Over time, these sources became insufficient. Therefore, the Government of Botswana commissioned the NSC to connect with developed and planned dams in the country's north-east to supplement water supply to the capital and other locations along the pipeline.

Sustainable yields of dams supplying water to Greater Gaborone are summarized in table 3.2. The yields are low compared to their capacity due to erratic river flows, high rates of evaporation (28.5 per cent higher than the sustainable yields) and limited dam site suitability.

Raw water from the dams in north-eastern Botswana is transported through the NSC, undergoes treatment at different waterworks before it is fed into the distribution system (see figure 3.14). The Mmamashia and the Gaborone Water Treatment Plants supply Gaborone and the connected demand centres. Efforts have also been put towards fully adopting integrated water resources management, a new paradigm shift for the efficient use of limited water resources rather than developing new ones.

It has been established that evaporation at Gaborone, Letsibogo, Shashe and Bokaa Dams is critical during reservoir sizing and its operation (Kenabatho and Parida, 2005). Despite construction of new dams to improve

Figure 3.14: Gaborone water distribution network




Source: Nono et al., 2019

water supply, the global increase in temperature is increasing dam water loss through high evaporation rates. This outcome has resulted in annual average reservoir evaporation rates for Gaborone and Bokaa Dams reported as 1,544 mm to a maximum of 2,001 mm per year. For the other dams, Letsibogo, Dikgatlhong and Shashe, the annual average reservoir evaporation is reported as 1,673 mm and could reach a maximum of 2,285 mm per year. The increased evaporation and decreasing precipitation over the country are partly responsible for reducing stored water in Botswana's dams (see figures 3.15 and 3.16).

### 3.2.6.1. Gaborone and Bokaa Dams

Gaborone was selected to serve as the country's capital partly because it had a river that could be dammed to supply adequate water to the new town. Construction of the Gaborone Dam started in 1963 and was completed a year later. By 1966 the reservoir had been filled with overflows. The dam was designed to serve 20,000 inhabitants, a figure that was almost tripled in less than 20 years (see table 3.1). Therefore, by 1980 the dam's water supply was deemed inadequate because of the rapid population increase, improved incomes and changing lifestyles. Consequently, between 1983 and 1985, the Government, with World Bank funding, raised the dam wall by seven metres in order to increase its reservoir holding capacity from 38 million to 141 million cubic metres (Kadibadiba, 2017). Despite this mesure, water supply challenges persisted due to the city's rapid population growth, growing affluence, construction activities and loss of water through evapotranspiration.

Evapotranspiration in Gaborone Dam (and other dams in Botswana) is exacerbated by low humidity, high temperatures and the dam's large surface and low depth characteristics. To augment the dam's water supply, it could receive 7 million $m^3$ of raw water from the Molatedi Dam in South Africa under an agreement signed in 1988. In addition, between 1990 and 1993 a new dam was built at Bokaa along the Metsimotlhabe River and approximately 40 km north of Gaborone Dam.

Volumes of water stored in the Gaborone Dam have been decreasing yearly. One of the severest droughts in the country's recent history was in 2015, during which the city's dam registered its lowest volumes and failed to function (see figures 3.15 and 3.16). This information is based on the period of available data.

Figure 3.15: Annual water volumes from water utility dams

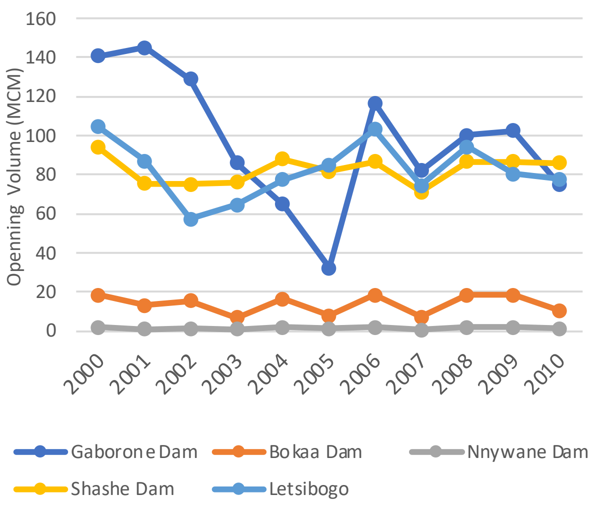
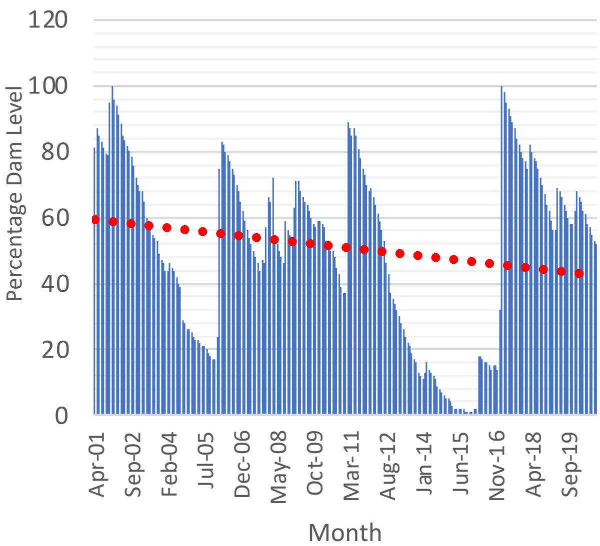



Figure 3.16: Gaborone Dam water levels 2001 to 2020




### 3.2.6.2. Molatedi Dam

Botswana has an annual water quota of 7.3 Mm³ from the Molatedi Dam in South Africa, which is reduced to half when the dam level is below 26 per cent (Statistics Botswana 2018). The total catchment area of the Marico River above its confluence with the Crocodile River has been assessed at some 11,500 km². Of this area, 3,058 km² is below the Molatedi Dam, of which some 1,234 km² comprises Botswana territory. The total catchment of the Molatedi Dam site is 8,422 km² of which 2,818 km² is upstream of the Kromellenboog and Marico Bosveld Dams (Swart et al., 2007).

### 3.2.6.3. Letsibogo and Dikgathong Dams

Given the ever-increasing demand for water in Gaborone and other settlements in the south-eastern part of the country, the Government decided to build two additional dams (Letsibogo and Dikgatlhong) some 360–400 km north of Gaborone. However, currently, only Letsibogo has started contributing to the Gaborone distribution network (see figure 3.14). At the same time, the 400 Mm³ capacity Dikgatlhong Dam, which exceeds all other dam capacities combined, is being connected to the NSC pipeline to increase water volumes drawn from southern Botswana. The whole NSC pipeline showing all the demand centres targeted, including Gaborone, is shown in figure 3.17. Attributes of the dams and those still to be linked through the NSC are summarized in table 3.2.

### 3.2.6.4 North-South Carrier Water Project (NSC)

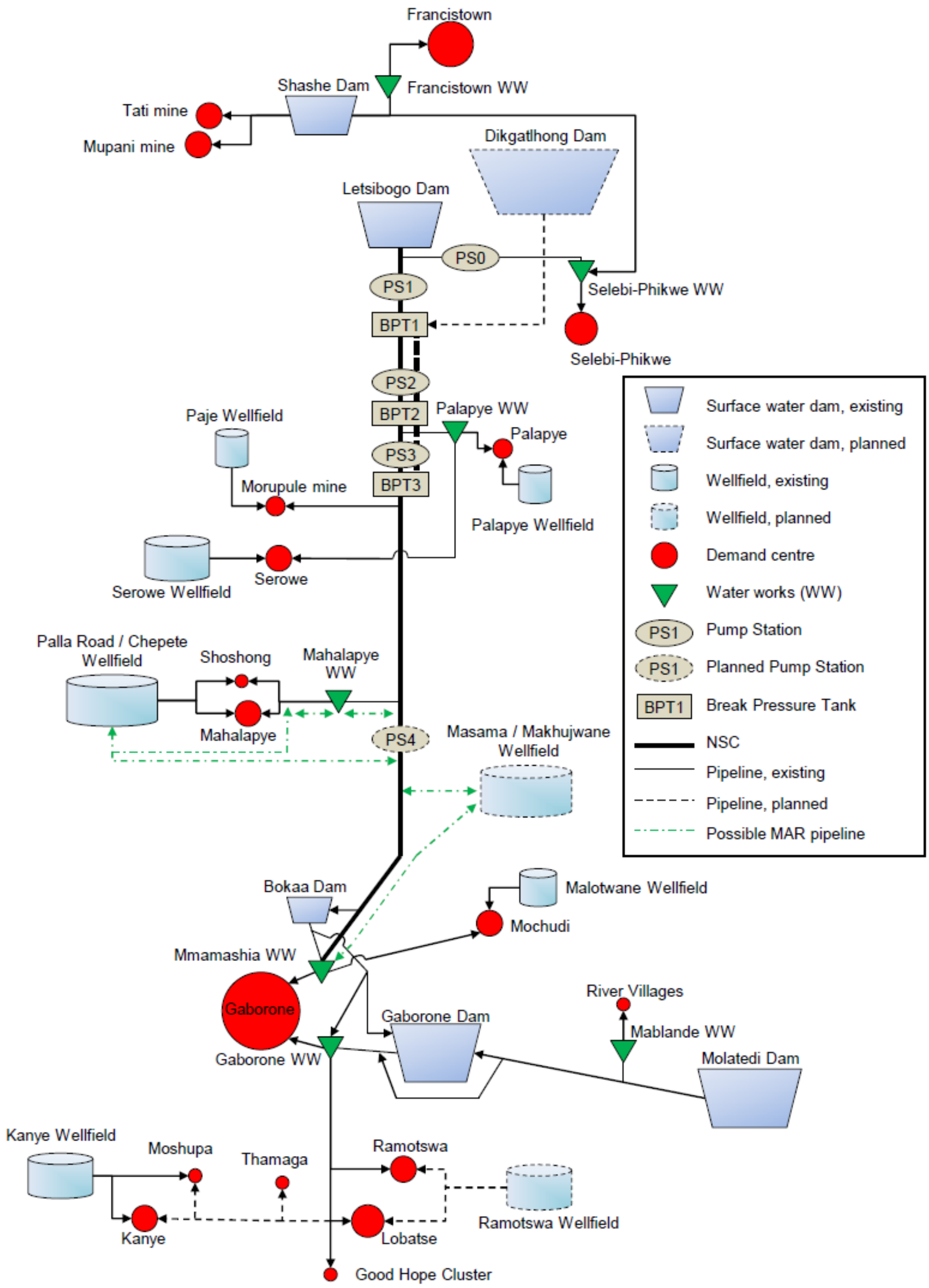
The NSC was commissioned in 2002. Mainly it was conceived to relieve the tight water demand in the south-east (Greater Gaborone) while supplying the central regions dependent on groundwater. The system consisted of 6 surface water dams, 8 wellfields, water transmission systems and water treatment works, 7 waterworks and 18 demand centres (see figure 3.17).

### 3.2.6.5 Groundwater resources

Curently, groundwater contributes about 10 per cent of water in Botswana's urban centres, while surface sources make up the remainder. This situation applies to the Greater Gaborone area. Over most of central, south-western and western Botswana groundwater has been the most critical water resource for many years since surface water resources are restricted to the country's east. When the NSC was commissioned in 2002, the Government adopted a policy to promote conjunctive water use schemes. The conjunctive use concept was meant to allow for good management practice at wellfields. The Ramotswa Wellfields were drilled in 1978 to supply water to Ramotswa village, about 34 km south of Gaborone. During the droughts of 1983 and 1984, the Government used the Wellfields as an emergency water supply source to supplement Gaborone (Ranganai et al., 2021). The Wellfields were connected to provide a capacity of 20,000 m³/d but supplied more than 8,000 m3/d (NWMPR, 2006) during those years. However, the plan to use groundwater from Ramotswa Wellfields to supplement Gaborone water was abandoned due to nitrate contamination of the Ramotswa aquifers.

For the NSC, the wellfields along and within the vicinity feeding into the pipeline should only be operated when the Letsibogo Dam levels are low and switched off

Figure 3.17: North-South carrier linkage to Greater Gaborone water supply system




Source: Lindhe et al., 2020

when dam water levels are high to allow groundwater resources to recover. The construction of the Masama Wellfields, approximately 100 km north of Gaborone City, was commissioned and included the design and construction of a raw water pipeline. This facility supplies 64,000 m$^3$/day to Mmamashia Water Treatment Plant near Gaborone. The main purpose of the pipeline is to augment supplies to water-stressed areas within the Greater Gaborone corridor, including the Lobatse/Barolong, the Thamaga/Moshupa/Kanye, Molepolole, Mochudi/Bokaa catchment areas.

#### 3.2.6.6 Wastewater resources

With wastewater constituting about 20 per cent of the country's available water resources (Government of Botswana, 2006), water recycling and reuse in Botswana is still limited to watering public gardens, firefighting and irrigating horticultural plants (Khupe, 1996). Use of effluent from wastewater treatment plants to irrigate crops for human consumption in raw form (for example, vegetables and fruits) is prohibited for a period of two weeks prior to harvesting (Ganesan, 1998). It is crucial for authorities to include wastewater management in their water supply, operation and maintenance budget.

#### 3.2.6.7 Chobe/Zambezi water resources

A proposal to extend the North-South Carrier Water Project to deliver raw water from the Zambezi River (900 km north of Gaborone) has been in consideration over the last 20 years. The proposed initiative will provide a lasting solution to water requirements for Gaborone and nearby settlements that experience water rationing during drought years. Most of the water transferred from the Chobe and Zambezi Rivers will, however, be used for irrigation at Pandamatenga.

Despite the country's ability to build several dams, water carrier pipelines and import raw water from neighbouring South Africa, all attributed to enduring and steady revenues from mineral resources and prudent use of the earnings, a new paradigm shift is needed to secure the country's future water sources.

## 3.3. RESPONSES TO WATER SCARCITY IN THE CONTEXT OF CLIMATE VARIABILITY AND CHANGE

### 3.3.1 Demand management interventions

The Gaborone Dam was designed to serve 20,000 inhabitants; the figure almost tripled in less than 20 years (see table 3.3). By 1980, the dam's water supply was deemed inadequate because of the city's rapid population increase, improved incomes and changing lifestyles. Consequently, between 1983 and 1985, the Government with financial support from the World Bank raised the dam wall by seven metres to increase the reservoir capacity from 38 million cubic metres to 141 million cubic metres (Kadibadiba, 2017).

As a country, national goals are also articulated clearly regarding water resources management within the context of limited water supply against rapidly increasing affluence and demand. The current National Vision 2036, for example, defines the goals and aspirations of Botswana towards "Achieving Prosperity for All". Integral to the realization of the ideals of this vision is water conservation and demand management by the sectors of the economy, and members of society for socio-economic advancement that do not compromise opportunities of future generations and the health of the environment. The tone for this is anchored on development of the Botswana National Water Conservation and Water Demand Management Strategy and the Botswana Integrated Water Resources Management and Water Efficiency Plans (IWRM-WEP). Botswana is currently reviewing this strategy, which is seen as a vehicle through which the country will be better positioned to achieve sound water conservation and demand management.

Evapotranspiration in Gaborone Dam (and other dams in Botswana) is exacerbated by low humidity and high temperatures and the dam's large surface and low depth characteristics. To augment the dam's water supply, Gaborone Dam could receive 7 million m3 of raw water from Molatedi Dam in South Africa under an agreement signed in 1988. In addition, between 1990 and 1993, a new dam was built at Bokaa along the Metsimotlhabe River, approximately 40 km north of Gaborone Dam.

In response to the 2015 drought, the Government had to rethink water security as a national priority by accelerating efforts towards strategic and participatory processes oriented towards water and sanitation provision for all. This strategy would result in prevention of illnesses and deaths related to waterborne diseases and economic losses. Other water demand management strategies introduced to curb water scarcity in Gaborone are shown in figure 3.18; these include wastewater reclamation, leak detection and a list of demand management measures.

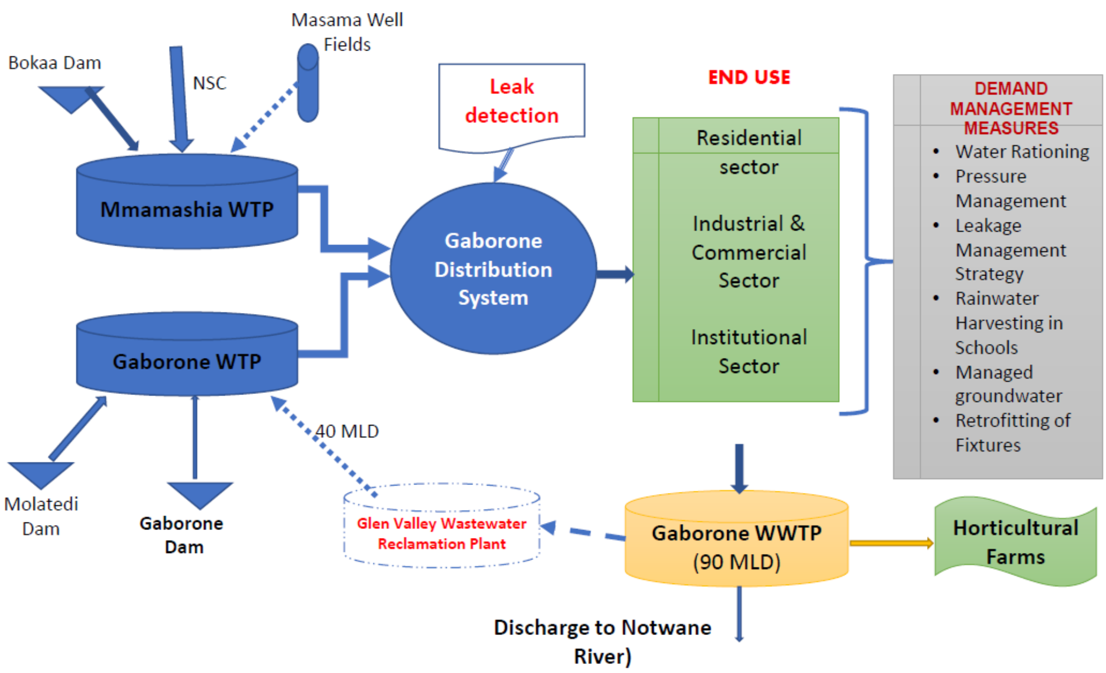
With regard to leakage detection, Gaborone city and the nearby town of Lobatse, which together are the core of Botswana's largest population cluster, have recently been zoned. This entails the installation of bulk meters and pressure-reducing valves at strategic points in the distribution system at which each meter records flow into a discrete zone that has been set up with a permanent boundary. This enables night flows into the zone to be regularly monitored for calculation of leakage levels, which can be monitored, attended to and managed and thus reducing water wastage. The results of this measure are yet to be fully realized for Gaborone city. The Water Utilities Corporation has engaged a private partner to operate, manage and maintain its 90,000 m3/day Glen Valley Wastewater Treatment Plant. Currently the facility operates at 40,000 $m^3$/day capacity. The scope of the works concluded with the private partner will include the development of a reclamation plant and transfer pipeline that will ultimately discharge 40 million litres per day of treated effluent into the Gaborone Dam Reservoir for blending before being fed into the existing Gaborone potable water treatment plant. This is anticipated to contribute around 20 per cent of water supply needs to Gaborone city and its immediate environments.

### 3.3.2 Institutional and regulatory framework

Proper and sound water service provision requires a supportive policy and a legislative and administrative framework. The framework provides the enabling environment through which its instruments can be harnessed. Equally important is an understanding of the existing policy, legislative and administrative framework. Such knowledge helps minimize inconsistencies and promotes the harmonization of approaches.

The Department of Water and Sanitation (DWS) and the Water Utilities Corporation are the foremost authorities in the country's water sector. The corporation is responsible for the provision of potable water nationwide and the management of wastewater treatment services. With the water regulator still to be established, the corporation is also responsible for financial sustainability across the water sector, reducing wastage by facilitating the streamlining of operations and determining revenue requirements to inform regular tariff adjustments. The corporation also oversees compliance of service standards to ensure efficiency and protect consumer

Figure 3.18: Water management strategies to curb water scarcity in Gaborone




Note: Dotted lines mean planned or under construction.

**Table 3.3: National plans and policies relevant to water management and supply**

| n/n | Water Sectors Plans & Policies | Objectives and Purpose |
|---|---|---|
| 1 | Botswana's Vision 2036 | The vision sets out long-term goals and aspirations of Botswana for the next 20 years. The national vision pillars point to a sustainable development pathway beckoning the balancing of social, economic and environmental objectives in line with the United Nations Sustainable Development Goals. |
| 2 | National Development Plan 11 of 2017–2023. | The plan outlines the Government's development priorities during the plan period for the different sectors of the economy including that of water. |
| 3 | The National Water Master Plan Review (NWMPR) of 2006 | Positions Botswana's water resources planning, development and management to move away from supply led to stewardship and water demand management with the aim of better managing and conserving the already mobilized resources. |
| 4 | Water Utilities Act of 1970 | Provides for the establishment of a corporation to be known as the Water Utilities Corporation for the supply and distribution of water. The Act establishes the Corporation as the water authority as proposed in the Waterworks Act that called for the establishment of water authorities in waterworks areas. The Water Utilities Act is currently under review. |
| 5 | National Water Policy | The policy objective is to provide a national framework that will facilitate access to water of suitable quality and standards for the citizenry and provide the foundations for sustainable development of water resources in support of economic growth, diversification and poverty eradication. |
| 6 | Agenda 21 | Calls for sustainable and environmentally sound development in all countries. Botswana has an action programme, which requires: (1) preservation, protection and improvement of the quality of the environment, (2) contribution towards protecting public health, and (3) ensuring a prudent and rational utilization of natural resources. |
| 7 | Botswana's policy for wastewater and sanitation management | It charts the way forward in implementing the declared programme of action stated above. The policy aims "to promote the health and well-being of the people of Botswana through the provision of appropriate and sustainable wastewater/sanitation management and to introduce mechanisms for the protection and conservation of water resources". |
| 8 | Gaborone City Council (General) By-laws (Cap. 40:02). | These general By-laws of the City Council of Gaborone regulate miscellaneous sectors including health and sanitation. |
| 9 | Gaborone City Council (Public Standpipes) By-laws, 1994 (Cap. 40:02). | By-laws regulate: (a) the use of water from a public standpipe: in designated areas; (b) use of water by persons other than occupiers of designated areas; (c) use of water from public standpipes; (d) withholding of supply of public standpipe water; (e) inspection of standpipes; (f) misuse of water; (g) damage to public standpipes, and; (h) pollution of standpipe water. (10 by-laws). |
| 10 | Botswana Climate Change Policy, 2021 | To mainstream sustainability and climate change into development planning and in so doing, enhance Botswana's resilience and capacity to respond to existing and anticipated climate change impacts. The policy also promotes low carbon development pathways and approaches that significantly contribute to socio economic development, environmental protection, poverty eradication and global goal for reduction of Greenhouse-Gases (GHG) from the atmosphere and SDG's. |

rights. On the other hand, the department is responsible for assessing, planning, developing and maintaining water resources for domestic, agricultural, commercial, industrial and other uses countrywide. Additionally, the department assists and advises on the formulation of water resources development plans, management policies and legislation. The depatment also serves as the secretariat of the Water Apportionment Board. Both department and corporation fall under the Ministry of Lands, Water and Sanitation Services (MLWS). Relevant plans, policies, legislation, guidelines, standards and strategies applicable to water services provision for Gaborone are briefly discussed in table 3.3.

### 3.3.3. Water demand management technologies

In order to prepare for future droughts and possible water shortages, the Government recognizes the need for innovative affordable technologies. Such technologies for collection, storage and treatment of harvested rainwater have been piloted across most parts of Botswana. Rainwater harvesting technology dates to 1979 when it was specifically used for a Government-aided Arable Land Development Programme (Gould and Jay, 1993). However, due to recuring droughts in the country, rainwater harvesting technonlgies have been installed in institutional (for example, schools) and commercial buildings in urban places as a major supplementary source of drinking water and irrigation requirements or whenever potable water supplies are depleting. The Botswana National Water Master Plan estimates that Gaborone has about 8.84 $mm^2$ of rooftop area that has the potential to generate about 3.77 $mm^3$ of rainwater.

One notable successful stormwater harvesting pilot study was at the Department of Water and Sanitation headquarters in Gaborone between 2009 and 2013. The plan was to harvest water from the combined rooftop and paved surfaces of about 1,647.5 $m^2$ areal spread. Looking at the volumes of harvested water that replaced potable water for non-potable use, the water bill was reduced by over half to P19006.58 from a potential bill of P40369.08. There are other rainwater harvesting schemes, especially in some government schools which are unfortunately not monitored despite their significant reductions of use of potable water in non-potable uses like gardening and cleaning, among others. One published postgraduate study that was completed recently, investigating potential for groundwater recharge using stormwater over the Notwane catchment that hosts Gaborone, identified areas with low elevations and high flow accumulation as great potential sites for capturing runoff in detention ponds and check dams at suitable sub-catchment outlet points and thus demonstrating another aspect in which stormwater which is otherwise considered a nuisance, can be used for managed aquifer recharge as a water security intervention (Tafila et al., 2022). The volumes collected from stormwater runoff and rooftops have the potential to contribute about 48 per cent of the total annual domestic demand.

The Coronavirus disease (COVID-19) pandemic has changed the way water is used and managed in schools nationwide. This has significantly reduced water bills as collected water has also found its way into gardening,

Figure 3.19: Some water management technologies adopted in Botswana: (a) Rooftop rainwater harvesting (b) Example of water management technologies installed at schools in Gaborone

(a)

(b)

and in some instances cooking for the pupils. Hygiene standards have also improved as water is very important within the context of COVID-19, among others. Figure 3.19.a shows a residential house connected with a rainwater collection tank while figure 3.19.b shows the specially designed water with wash basins for pupils. This system involves the use of gutters to collect rooftop rainwater and direct it to a storage tank. The stored water can then be used for non-potable purposes, such as watering plants, washing clothes, and flushing toilets. The system may contribute to high water consumption in the future.

The other technology that has also gained interest in the country is artificial recharge of groundwater technology known as managed aquifer recharge. This technology is meant to secure high quality water resources by facilitating infiltration of rainfall and treated wastewater (Lindhe et al., 2020). The purpose of the technology is to prevent water loss by evapotranspiration and secure water resources. However, the technology is still at trial stage and not yet fully implemented.

To overcome the lack of economically viable dam sites in Botswana, underground storage of surface run-off water is one technology that has been proposed in the past (Lindhe et al., 2020). This technology could allow Botswana to harvest additional water, thus improving water security. In addition to the technical challenges, groundwater abstractions require a more stringent regime of monitoring the use of aquifers being recharged through this technology. Because of its complex management requirements this technology has not yet been implemented in Botswana.

### 3.3.4. Financial management and costs

Water supply to Gaborone is costly. Currently, the main source of water to the city is Gaborone Dam (capacity; 142 million cubic metres - MCM), supported by Bokaa Dam (capacity; 19 MCM) and Letsibobo Dam (capacity; 104 MCM via the North-South Carrier pipeline). The Government also has an agreement with South Africa on abstractions from the Molatedi Dam. But these measures are not enough. The host Limpopo catchment is very important in terms of water availability and supply since all the major dams are within the basin. An inter-basin water transfer, the a 400-km North-South Carrier pipeline carries water from the country's northern part to the drier south (including Gaborone) with cost implications.

In 2017, Botswana received a USD 145.5 million World Bank loan captioned the Botswana Emergency Water Security and Water Efficiency Project. The project aims at improving availability of water in drought vulnerable areas, increase the efficiency of WUC, and strengthen wastewater management in selected systems. The project is ongoing and implemented under the following components:

1. Improve availability of water supply and efficiency of services (USD 114.05 million)

2. Improve wastewater and sludge management (USD 21.65 million)

3. Sector reform and institutional strengthening (USD 20.75 million).

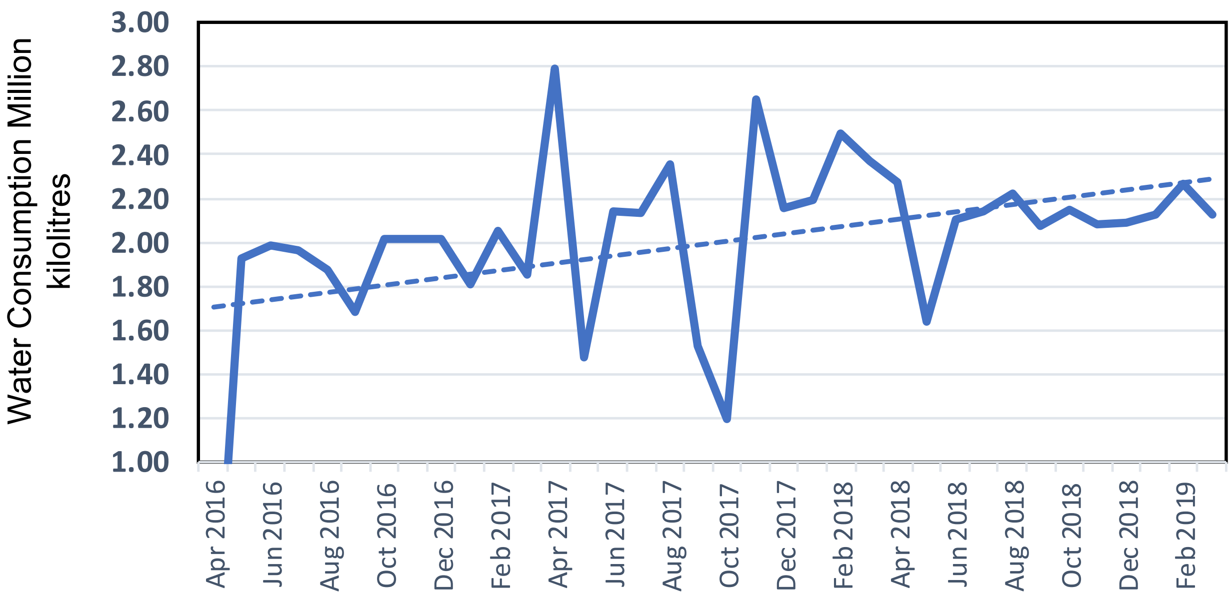
Currently, the anticipated Masama wellfield connection project is nearing completion at 2 billion pula (about USD 149 million) under component (1). The project enables Government to deliver water to water-stressed Gaborone and its surroundings as well as to 23 settlements over south-eastern Botswana, including Molepolole and its surrounding areas. Once the Masama 100-km pipeline project starts supplying water to the Molepolole project, known as the Gamononyane Pipeline, the 23 Goodhope villages water projects will also begin. These are all villages within the greater Gaborone area. Various components of the North-South water carrier "sub-level 2.2" were awarded recently. The Mmamashia to Kgale and Kgale to Lobatse are two such components. They are less than 100 km in length with each costing over 1 billion pula (USD149M). Currently, plans are at advanced stages under component (2) with upscaling of wastewater reuse and possible connections into especially the Gaborone distribution network. Botswana is also reviewing its National Water Conservation and Demand Management Strategy under component (3) of the World Bank Project.

In addition to loans acquired externally, the Government provides domestic funds for its water resources management and development through national plans. The Government has a social responsibility to develop and mobilize the right quantities and quality of water to its people. This responsibility falls on the Department of Water and Sanitation and the Water Utilities Corporation, under the Ministry of Land, Water and Sanitation Services. Once the water is mobilized, the responsible water authority manages the transactions on behalf of the Government.

**Table 3.4: Water production and sales for Gaborone Management Centre and others**

| n/n | Management Centre | Population | Number of connections | Water Production (Kl) | Sales of water (Kl) | Revenue (USD) |
|---|---|---|---|---|---|---|
| 1 | Gaborone | 371 584 | 78 695 | 24 435 785 | 20 792 005 | 32 019 688 |
| 2 | Lobatse | 147 006 | 28 547 | 6 891 735 | 3 747 109 | 5 770 548 |
| 3 | Selebi Phikwe | 131 900 | 26 849 | 11 119 405 | 8 560 012 | 1 182 418 |
| 4 | Francistown | 176 000 | 35 791 | 15 889 994 | 10 800 676 | 16 633 041 |

Figure 3.20: Billed water consumption for Gaborone Management Centre




Source: Water Supply and Demand, Botswana 2018.

In terms of cost recovery, this is realized by charging users for water supply and thus indirectly helping the Government maintain the water supply infrastructure. Table 3.4 shows revenue collection from water sale in Gaborone and other major Botswana cities, while figure 3.20 denotes the increasing trends of the water consumption that has been billed. Botswana currently uses increasing block tariff structure in which consumers pay as per the amount of water used within the block they fall. Therefore, in Gaborone, the cost of water consumption of amounts greater than 25 $m^3$/month/connection is about USD 1.54. The lower water users, who are mostly underpriviledged residents, pay less per unit consumption than the greater consumers. This elasticity is good in that it caters to those who can barely afford to pay for water and those who can afford more usually use large quantities for which charges per unit consumption are high. So this offers a good balance between availing water to all and at the same time making people pay for the services and thus generating revenue. Since the Government has drastically reduced public standpipes and restricted access to the few remaining to pre-paid card holders, water wastage by residents who hitherto received the service free has been reduced. Leakages in the distribution networks, for example through broken faucets, is mostly constrained to individual households who promptly report faults to avoid paying for wasted water.

The revenue generated in relation to water sales is depicted in table 3.4. These costs are high due to higher costs of transport through the NSC pipeline. The envisaged second NSC is expected to escalate water supply costs. The higher the block, the higher the charge per unit cost. This then balances between providing affordable water to the disadvantaged and making sure that those who use more water pay more for sustaining of operations of the Water Utilities Corporation and infrastructure. This tariff structure appears to have served Botswana well, and it is likely to be maintained into the future.

Related to the tariff structure, revenue collection is enhanced by a Water Utilities Corporation application through which consumers can submit their monthly water consumption figures for billing. This reduces, if not eliminates, the need for the utility's agents to read meters at each household. The use of pre-paid tokens and cards to use public standpipes is also designed to maximize revenue and cut wastage. This is being applied mostly in towns and large villages.

## 3.4. IMPACTS AND CONSTRAINTS

With the NSC becoming the main hope for future sustainability of water supply in Gaborone, finances will be needed for its expansion, including drawing water from Dikgatlhong Dam and the Zambezi River. The Government is connecting the Masama wellfields about 90 km to the north of the city to augment the water supply.

Since all of Botswana's river catchments are transboundary, two large-scale inter-basin and national water transfer schemes have been considered to secure and increase new water resources. The Chobe-Zambezi Water Transfer Scheme was initially proposed to withdraw water from the Chobe and Zambezi Rivers through a 581-km pipeline and supply 495 $Mm^3$ of water annually to the Pandamatenga region for agricultural development. Another scheme includes the Lesotho-Botswana water transfer, which would supply 200 $Mm^3$ of water to Botswana through a 700-km pipeline from relatively water-abundant Lesotho, which is currently undergoing a feasibility study in the Orange-Senqu River Commission (ORASECOM). Estimated costs of all these transfer schemes are prohibitive. The estimated costs of all these transfer schemes are prohibitive. For example, the most prioritized future Chobe-Zambezi transfer scheme will cost an estimated USD 2.9 million. This is the most costly of all the proposed projects and accounts for about 80 per cent of the overall costs (USD 3.5 million) of the proposed future water resources projects (MLWS, 2018). The "cheaper" options available to Botswana include wastewater reuse, which is in fact not as cheap. Rainwater harvesting has not been fully explored and remains one of the key recommendations from the Botswana National Water Master Plan Review of 2006. There are several technologies available for rainwater harvesting in Gaborone; these include, rooftop rainwater harvesting, ground-based rainwater harvesting and surface runoff rainwater harvesting. The rooftop rainwater harvesting is the most popular and widely used system. These technologies provide a reliable source of water for non-potable purposes and can help alleviate the city's water shortage.

## 3.5. SUSTAINABILITY AND REPLICABILITY

Transporting water to Gaborone through NSC, as the main water source, is for the short and long term. The NSC will be further expanded by tapping water from the Zambezi River. Refurbishment and development of a reclamation plant and transfer pipeline from the existing 90,000 $m^3$/day Glen Valley Wastewater Treatment Plant will relieve pressure from the NSC and thus cushion the water supply system from the cost of transporting water over long distances. The plant is to treat Gaborone's effluent that will be discharged into the Gaborone Reservoir for blending before being fed into the existing Gaborone potable water treatment system. This measure will meet about 20 per cent of Gaborone's water demand in the medium- to long-term. Despite connection of the Masama wellfields to supplement the water supply to Gaborone, this is thought as insignificant as compared to the NSC and the anticipated wastewater reuse. It is, however, this conjunctive water use blended with wastewater reuse that offers diversified water sources, which balances risks into the future.

## 3.6. OUTSTANDING ISSUES

Botswana has embarked on water conservation and demand management measures of different scales (from pilot, regional to national scale) on rainwater harvesting, grey water reuse, treated wastewater reuse for irrigation, pressure management and implementation of water restrictions. It is high time that these measures were escalated from being pilot projects and rolled out with clear directions. The cost of these initiatives will, however, remain a challenge. The potential for large-scale and regional wastewater reuse and storm water collection has received little attention, yet they are a potential water source for the country. In order to reduce water demand, a deliberate effort within the water sector is needed to focus on the above-mentioned issues. Involvement of the private sector, research institutions and civil society remain key if Botswana intends to build a water-wise and secure climate-resilient society by 2036, as envisaged by the country's vision 2036.

## 3.7. SUMMARY OF FINDINGS

As reflected in the Botswana National Water Master Plan (2016), the planning philosophy of the country is anchored on improving aspects of sound water demand management and stewardship that appear to have been overlooked in preference of infrastructural development. Careful balancing of infrastructural development with the conservation of already limited and mobilized water resources can take the country into the future (Botswana Government, 2006; Parida and Moalafhi, 2008b).

Since Gaborone continues to experience increasing water demand, the cost implications of sustaining, expanding and maintaining the NSC are inevitable. The addition of wastewater reuse will contribute some 20 per cent of the water supply to the city, which will relieve pressure from the NSC and subsequently help reduce the costs of this inter-basin water transfer. Masama wellfields, some 100 km north of Gaborone, could also be used with some planned aquifer recharge to increase their contribution, especially when dam levels are low. The efficient use of water and the exploration of alternative water resources (rainwater harvesting, greywater recycling, treated effluent utilization and water desalination ) are key factors for ending water scarcity.

Currently, rainwater harvesting and water desalination are also starting to receive more attention as important components of water supply improvement. Water desalination has helped over the western and more arid parts of the country characterized by saline water. However, the practice has not been used to its utmost as most desalination plants are usually abandoned when some freshwater alternatives become available. Also, the desalination plants have been plagued with high operational and maintenance costs.

Most of the groundwater resources, especially those across western Botswana, have been abandoned due to salinity. In instances where desalination is under way, the processes have been inefficient, leading to the abandonment of most such undertakings. But with water options becoming limited, desalination technology might be revisited within the framework of advancements in technology for possible improvements. Recently, a multimillion-pula borehole water desalination plant was built at Rappelspan and Struizendam in the Kalagadi District, south-western Botswana, where groundwater resources are limited, very deep and mostly high in salt content. Other small-scale, pilot solar-powered water desalination technologies have been tried. Evidently, apart from rainwater harvesting technologies, water desalination technologies are also starting to receive more attention as important components of water supply improvement. However, the efficiency of these plants has been questionable and found to incur high operation and maintenance costs.

National goals are also articulated clearly regarding water resources management within the context of limited water supply against rapidly increasing affluence and demand. The current National Vision 2036, for example, defines the goals and aspirations of Batswana towards "Achieving Prosperity for All". The four pillars in achieving this include sustainable economic development, human and social development, sustainable environment and governance, peace and security. These pillars are embedded within tenets of water conservation and demand management by the sectors of the economy and members of society that support social upliftment, ensuring sustainable utilization of natural resources and support for good governance and water security.

## 3.8. CONCLUSIONS AND WAY FORWARD (LESSONS LEARNED)

Botswana has been successful in building several dams and exploiting groundwater resources, and construction of the North-South Water Carrier pipeline to curb water shortage and high water demand in the southern part of the country. This activity is in addition to the importation of raw water from South Africa for socio-economic advancement. This outcome has been possible due to enduring and steady revenues from mineral resources, prudent use of the earnings and sustained revenue collection from water sales. However, despite all these successes, the water supply to Gaborone is vulnerable to impacts of climate change and increasing demand, as is the case with the entire country. Therefore, a new paradigm shift is needed as mineral revenues decline along with available water resources in the face of increasing demand. As a result, options for new or alternative water sources are shrinking or becoming more expensive. For example, one of the highly considered and investigated alternatives to augment the current water supply is the large inter-basin and international transfer scheme, but costs involved are prohibitive. The transboundary nature of most of these water schemes makes the exploitation of these resources difficult, as they are subject to international water protocols. It is, thus, critical that efforts are made towards intensification of water conservation and water demand management if water efficiency and security for Gaborone are to be attained without compromising future prosperity.

It is, therefore, not surprising that water resources planning in Botswana is premised on a new paradigm shift. This paradigm rests on the premise that to satisfy future water demand strategies to this end will be dominated by issues of water resources stewardship and water demand management rather than capital development works (Botswana National Water Master plan (2006); Parida and Moalafhi, 2008b).

The following are key insights and lessons learned for sustainable water supply to Gaborone within the context of Botswana at large:

- Limited use of technology in managing supply and demand, including water treatment technologies, has yielded positive results that offer promise if appropriately assimilated into water resources management and planning.

- Rainwater harvesting knowledge and technologies have also increased over time, although efforts are still fragmented. The technologies, if fully implemented, can help in a major way.

- Further opportunities are available to use socioeconomic instruments to reduce and manage demand.

- The Government's reduction of public water standpipes and upgrading of some to use prepaid tokens and cards is a good initiative in helping to reduce water wastage and generate revenue for sustaining and maintaining water supply infrastructure and services.

- The water sector is moving towards improving digitalization of its business processes and service delivery. The Water Utilities Corporation uses an app for monthly remote reading of consumption, through which consumers take the readings and submit through the app. This process has improved the level of bill collection to close to 75 per cent in Gaborone. Pressure management and leak detection measures in Gaborone's water distribution networks are two of the options that should be fully implemented to reduce water losses significantly.

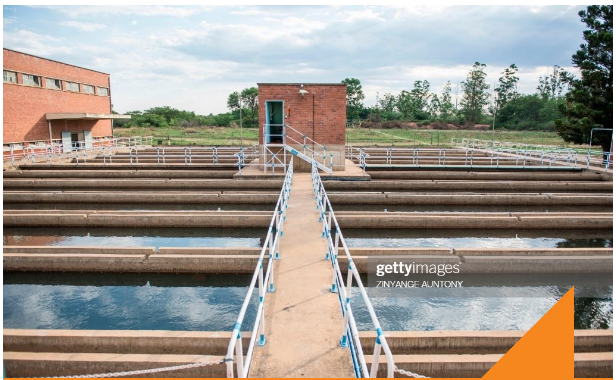
- The Covid-19 pandemic can be a lesson for all water utilities to improve services such as the use of smart metering.

- It is inspiring to learn how China has easily accessible good quality data for an extended period. This situation makes decision-making and research more meaningful. One hopes we can reach such a level. Public-private partnerships appear to work well in Zambia and Namibia on water markets and managed aquifer recharge, respectively.

There is need for greater collaboration with Zimbabwe, with which Botswana shares most of its transboundary water resources, especially for use of water from the Zambezi River.

CHAPTER 4

# Adjusting city water supply in view of climate change: the case of Lusaka

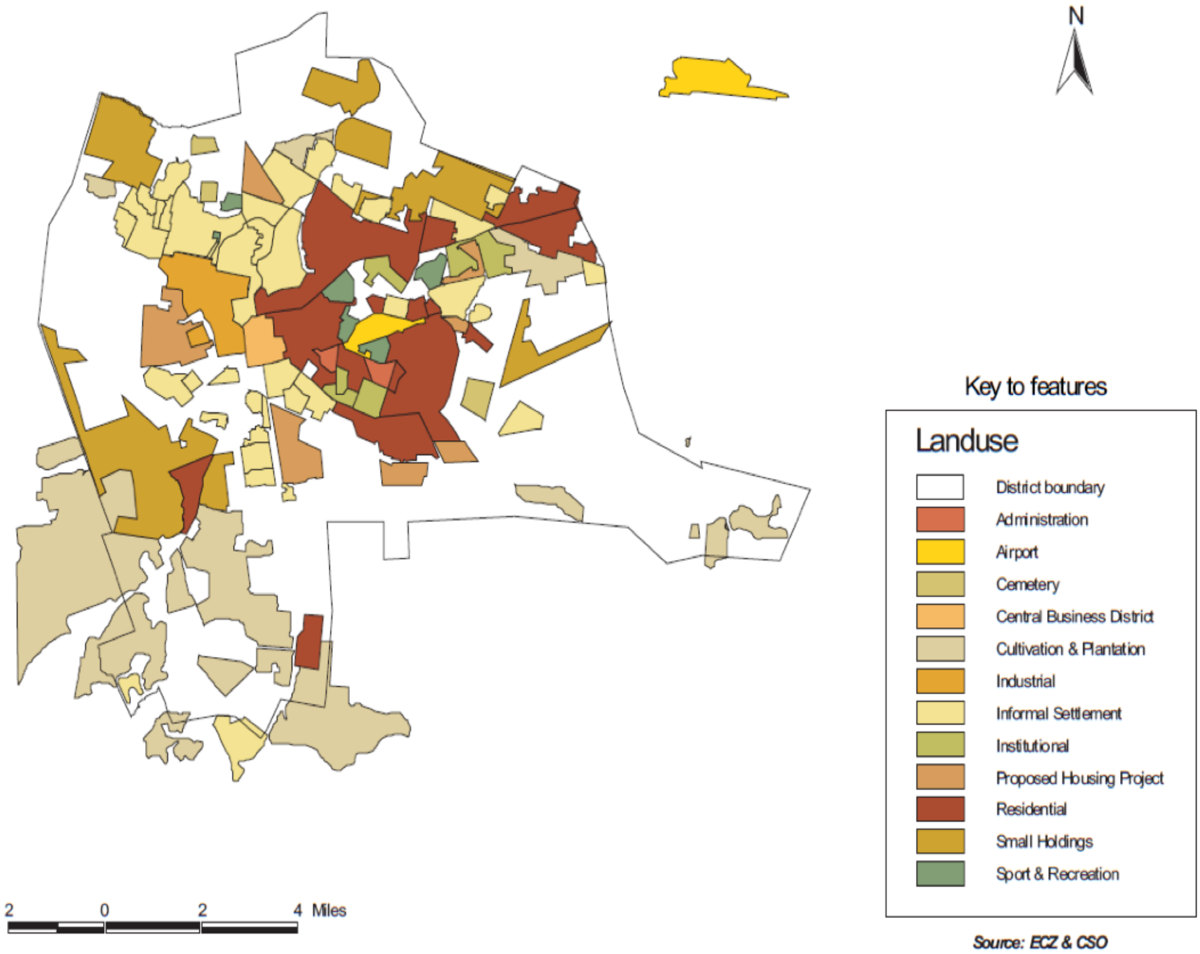



A case study by Eng. Kelvin Chitumbo and Dr Wilma Nchito

## 4.1. INTRODUCTION

Lusaka lies 1,600 km south of the equator at S15.41° and E28.29°, 1,280 metres above sea level. It has a metropolitan area covering approximately 360 km², and the city continues to sprawl rapidly beyond its official boundaries. After the nation gained independence in October 1964, the city experienced an unprecedented influx of people in the following years. This influx was due to the lifting of restrictions in place during the colonial era to regulate the migration of indigenous Zambians into urban spaces. According to the last census, in 2010, Lusaka had a population of approximately 1.8 million people, while population projections for 2011 to 2035 put the 2021 population at 2.8 million (Zambia Statistical Agency, ZSA 2013). The most recent census held in 2022 (the delay was caused by Covid-19 and presidential elections) state that Lusaka has a population of 2.2 million people. This is lower than the projected population. Lusaka now accounts for about 28 per cent of the country's urban population. The total urban population is 7.844,628. Lusaka's growth has encroached into areas that formerly provided much-needed ecological services such as groundwater retention. It is evident, for instance, from the changing groundwater table and the shifting summer season that the city has already been impacted by climate change. This case study presents the current state of affairs and possible solutions to the challenges facing Lusaka.

Figure 4.1: Lusaka city boundary and land use




Source: Lusaka City Council, 2008

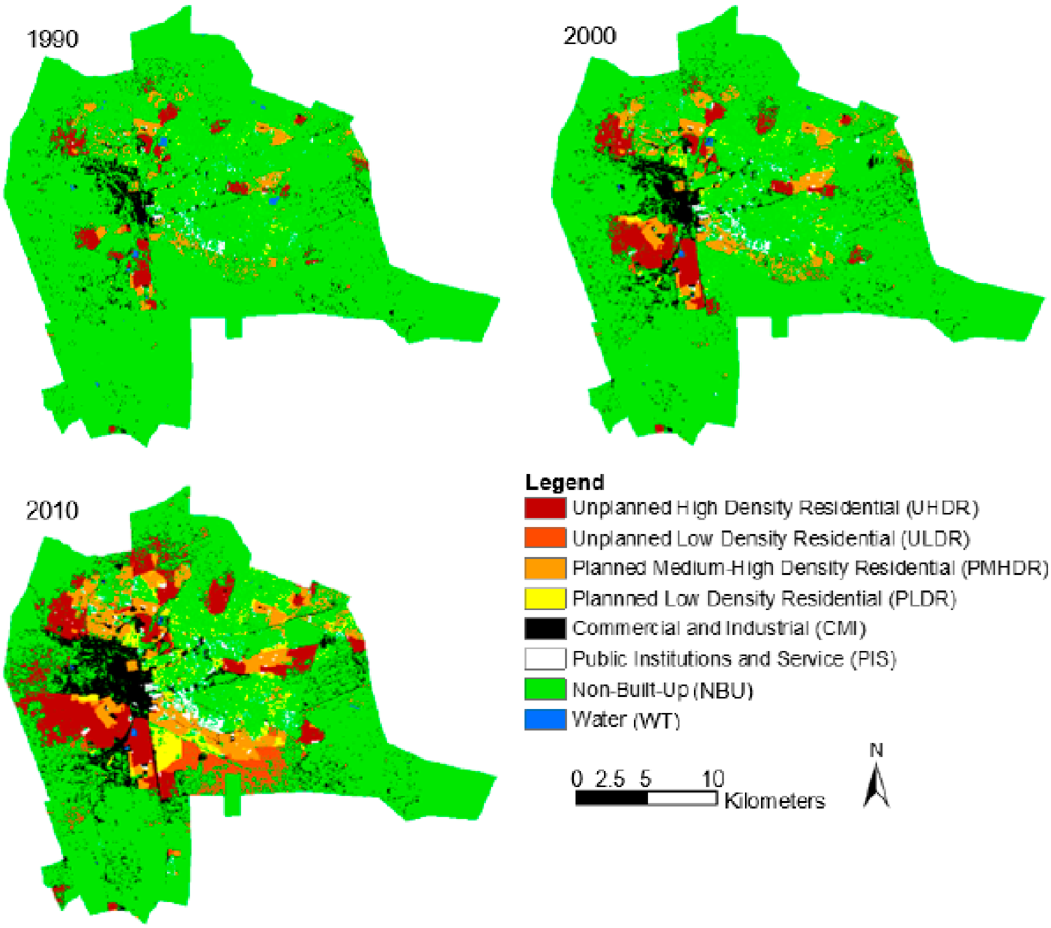
## 4.2. ESTABLISHMENT OF LUSAKA AND IMPACTS OF CLIMATE CHANGE

Lusaka was designated as the capital of the protectorate of Northern Rhodesia in 1931 due to its central location. The town was originally a siding along Cecil Rhodes' railway line intended to connect Cape Town (South Africa) to Cairo (Egypt). Railway sidings were created at 32-kilometre (20 miles) intervals along the Lusaka line in October 1905 (Kay, 1967). The siding had initially been at the 29-kilometre mark, but the flat limestone and vast farmland surrounding Lusaka was preferred. The site was originally a small village called Lusaaka, hence the origin of the name. Once the siding was established, the area attracted European settlement because of cheap arable land. A management board was established in 1913, giving the village an official administrative status. In 1928, the settlement comprised 282 Europeans and 1,596 indigenous people. The population at the time consisted mainly of villagers and a few settler shopkeepers and farmers. The Lusaka Township Regulations were formulated in 1922 "in recognition of the expanding needs of the evolving settlement" (Williams, 1986b) when the railway siding surrounded by farmland was declared a township. In 1929, the Township Ordnance and the Town Planning Ordnance were put in place to guide the settlement's administration, and in 1931 it was selected as the country's capital. However, it was only officially opened as the capital in May 1935, the delay being caused by the Great Depression (Sampson, 1971; Williams, 1986b). The location was a poor choice for a capital as it sits mostly on semi-pervious limestone and karst, making it prone to seasonal flooding. Unlike other African capitals, Lusaka was not established as an administrative centre, but its central location gives it high accessibility to the different parts of the country. Lusaka became a municipality in 1953 and was conferred a city by Royal Charter in 1960 (Williams, 1986b). The city's legal boundaries have expanded and the actual urban developments have exceeded these limits (see figure 4.1).

However, in recent years the city has been facing warmer temperatures with peaks of 40 C recorded, particularly in October. There is evidence of the effects of an urban heat island being felt, although there have not been specific studies of this phenomenon. The city is becoming more built up, and green spaces are quickly diminishing. This factor contributes to flash flooding, which is becoming more frequent. The satellite imagery of the city shows an expanding built-up area indicative of urban expansion. The images show the spread of the city's extent over 35 years (1984–2019). Between 2000 and 2007 the city's built-up area increased from 43.5 to 63.7 per cent of the total land area of Lusaka (GRZ, 2009) see figure 4.2. The city also conspicuously lacks a distinct green belt that can restrict further expansion. Although Lusaka has a long history of floods due to a naturally high water table, the flooding incidents are now more prolonged and affect more people. Tropical thunderstorms are becoming more intense, and rainwater cannot permeate quickly into the ground. These events cause flooding, which was predominantly in unplanned settlements but is now also occurring in formal areas located on marshes and *dambos*[5]. The effects of this are felt more by the poor as they have fewer options for mitigation than those in formal areas. People in formal areas can make structural changes to their homes or move from their flooded homes until waters subside.

Longer dry spells and reduced precipitation are also occurring in the city and within the region (Libanda and Ngonga, 2018). The city is indirectly affected by these dry spells, which sometimes result in poor crop yields in the regions that supplies the city with food. This result, in turn, leads to an increase in the city's food prices, hitting the poor the hardest. Moreover, the increased intensity of rains reduces the infiltration rates resulting in increases in the amount of run-off.

Figure 4.2: Urban land-use maps of Lusaka for 2000 and 2010




Source: Simwanda and Murayama, 2017

According to current population projections, Lusaka is among the fastest-growing cities in Africa (Fröhlich, 2019; Ashraf et al., 2018). The projected increase in population and changing climatic conditions call for concerted effort and deliberate attention to the issues of water and climate change. Failure to do so would result in the future population living in a city prone to acute water scarcity. Such an outcome would put many people at risk of contracting diseases. It would also threaten livelihoods, owing to diminished business resulting from inadequate water supply. Despite having better indicators than countries with similar economies to Zambia, the number of people who do not have access to safe water and sanitation is increasing in the country (Foster and Dominguez, 2010). It is estimated that only 30 per cent have access to potable water, and 13 per cent have access to sanitation. The rapid population growth and the sprawling nature of urban expansion make water supply expensive and complicated. Being heavily dependent on groundwater, Lusaka presents a good example of what needs to be done to ensure water security for cities. As the city becomes covered in concrete and other impervious materials from the numerous construction projects, it is also becoming drier. Surfaces such as paving stones, tarmac and built infrastructure result in reduced aquifer recharge, hence increasing the frequency and intensity of flooding. The hard surfaces cause rainwater to run-off into natural or man-made channels, bypassing aquifer recharge zones. One of the solutions to this situation would be to employ water-sensitive urban designs that consider pervious surfaces and constructed wetlands to facilitate groundwater recharge.

This case study is  necessary because Zambia has also experienced low electricity generation due to low levels of water in the Kariba Dam, which since its completion in 1959 has been a source of hydroelectricity for the whole country. Additionally, the city needs alternative energy to deliver water to its residents.

### 4.2.1 WATER SUPPLY CHALLENGES IN LUSAKA

Lusaka is experiencing a rapidly growing population. This means that more people continue to live in and around the city with a corresponding demand for potable water. The water supplied by the commercial utility is unable to meet demand. This pressure is causing residents to seek water from other sources, such as boreholes and shallow wells. Accordingly, this "self-supply" by residents means the utility cannot expand its resource base. Nussbaumer et al (2015) cite a 2004 publication by De Waele et al. stating that Lusaka had between 3,000 and 4,000 boreholes at the time and that most were not submitted for monitoring.

The low rate of service provision for water and sanitation services threatens groundwater quality through contamination due to the extensive use of pit latrines in the city's unplanned and unserviced areas. It is estimated that 90 per cent of the residents in unplanned settlements use pit latrines (ADB, 2017). These are discussed in the following sections.

### 4.2.2. Population growth trends and urban development dynamics

Zambia's population was estimated to be 19.6 million in 2020 (ZSA, 2013). Of that, 40 per cent lived in urban areas in the same year (ZSA, 2013). Currently, Lusaka hosts 25 per cent of the country's urban population. The city's population rose rapidly immediately after independence when colonial restrictions on Africans moving to the capital were removed. The median age is 16.8 years (ZSA, 2013), showing the city's youthful population.

The city's population continues to grow and is projected to reach 4.3 million by 2030 and 5.2 million by 2035 (see table 4.1). The population growth rate at 4.8 per cent is the highest in Lusaka at 140 people per square kilometre (ZSA, 2022).

The projections clearly overestimated population growth and when the census was carried out in 2022 the population of Lusaka was 2,204,039. It is, therefore, likely that the population projections for 2030 and 2035 will also be lower.

**Table 4.1: Lusaka's population 1950–2035**

| Year | Population |
|---|---:|
| 1950 | 31 000 |
| 1960 | 91 000 |
| 1970 | 278 000 |
| 1980 | 533 000 |
| 1990 | 757 000 |
| 2000 | 1 073 000 |
| 2010 | 1 747 152 |
| 2020 | 2 733 590 |
| 2030 | 4 267 000 |
| 2035 | 4 560 560 |

Source: ZSA, 2013

Figure 4.3: Districts in Lusaka Province


Source: Google Maps (https://www.fao.org/in-action/food-for-cities-programme/pilotcities/lusaka/en/)

This variation is due to the different land uses found in the city, which range from agriculture to densely populated, unplanned settlements. The city was planned for a much smaller population, and the water supply infrastructure has been unable to keep pace with the rapid expansion. The growth rate is projected to continue at about 4.8 per cent. The percentage of the population living in large urban areas has been increasing steadily. Although exact recent figures are unavailable, older ones show the population in large urban areas had risen from 18 per cent in 1963 to 28.2 per cent in 1980 (see table 4.2). This indicates that the larger urban areas are hosting an increasing number of citizens who need more services.

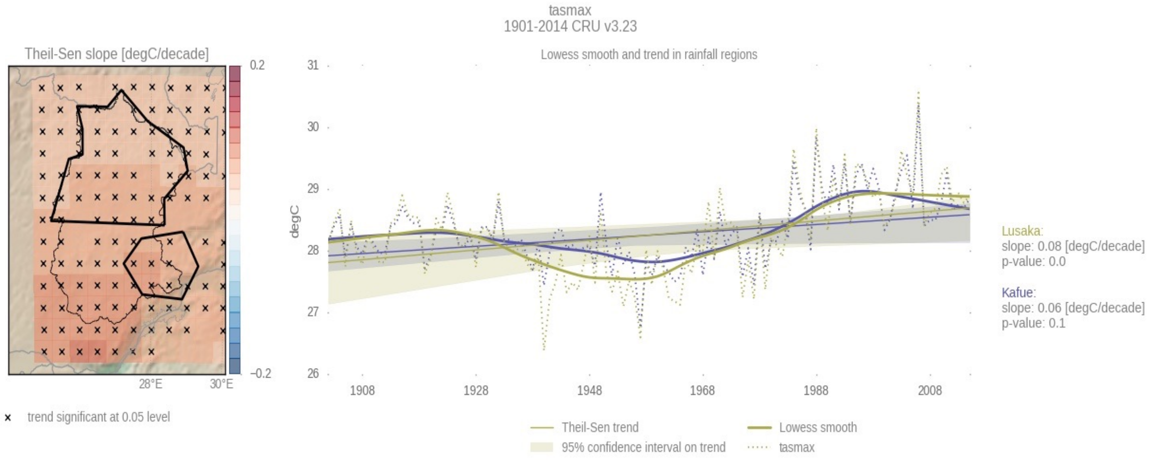
UN-Habitat predicts that Lusaka will be among Africa's five fastest-growing cities in the next 10–15 years (FCFA, 2016). The city is surrounded by the districts of Kafue, Chongwe, Chilanga and Chibombo (see figure 4.3). Chongwe and Kafue have higher populations and more economic activities for which they rely on Lusaka. The water utility services both towns.

### 4.2.3. Climate change models of the region and city

Lusaka's climate is warm and temperate, with minimal rain in winter. The average annual temperature is 20.3°C, and the average yearly rainfall is 831 mm/year. The city is getting warmer and drier due to climate variations. Spatial and seasonal variability is being felt through longer and hotter dry periods. Climate scientists predict that temperatures in Lusaka will likely increase by 1°C or 2°C in the next 10 years (FRACTAL, 2018). This scenario will be compounded by reduced rainfall and extreme weather events. The city typically experiences minimum temperatures of around 7.8°C in the cool months and maximum temperature of 31.7°C in the warmer months.

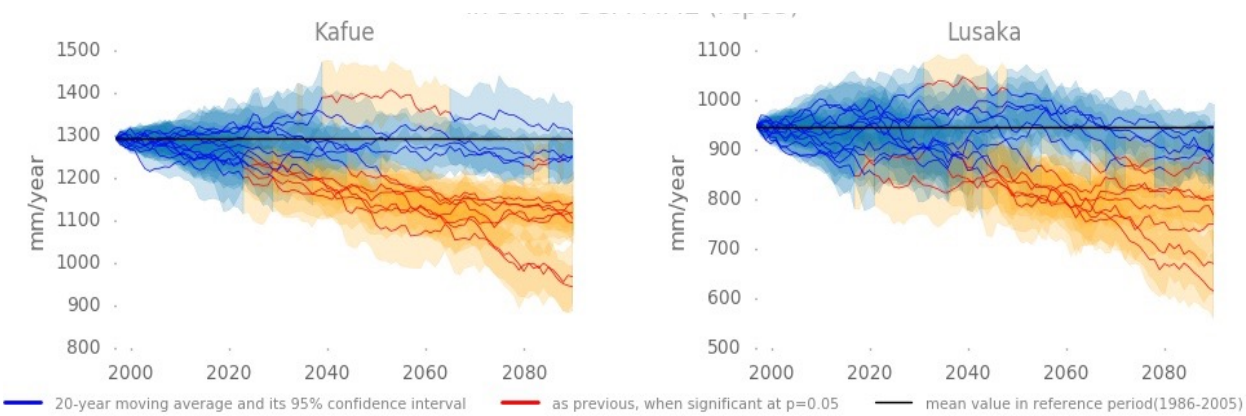
A historical trend analysis of temperatures in the city shows that there has been an increase of 1 degree Celsius in 100 years (see figure 4.4). This aligns with global average temperature increase (Vairavamoorthy, 2008). Localized climate models show

Figure 4.4: Lusaka temperature increase in the last 100 years




Source: CSAG/FRACTAL, 2018

Figure 4.5: Rainfall Projections in Kafue and Lusaka



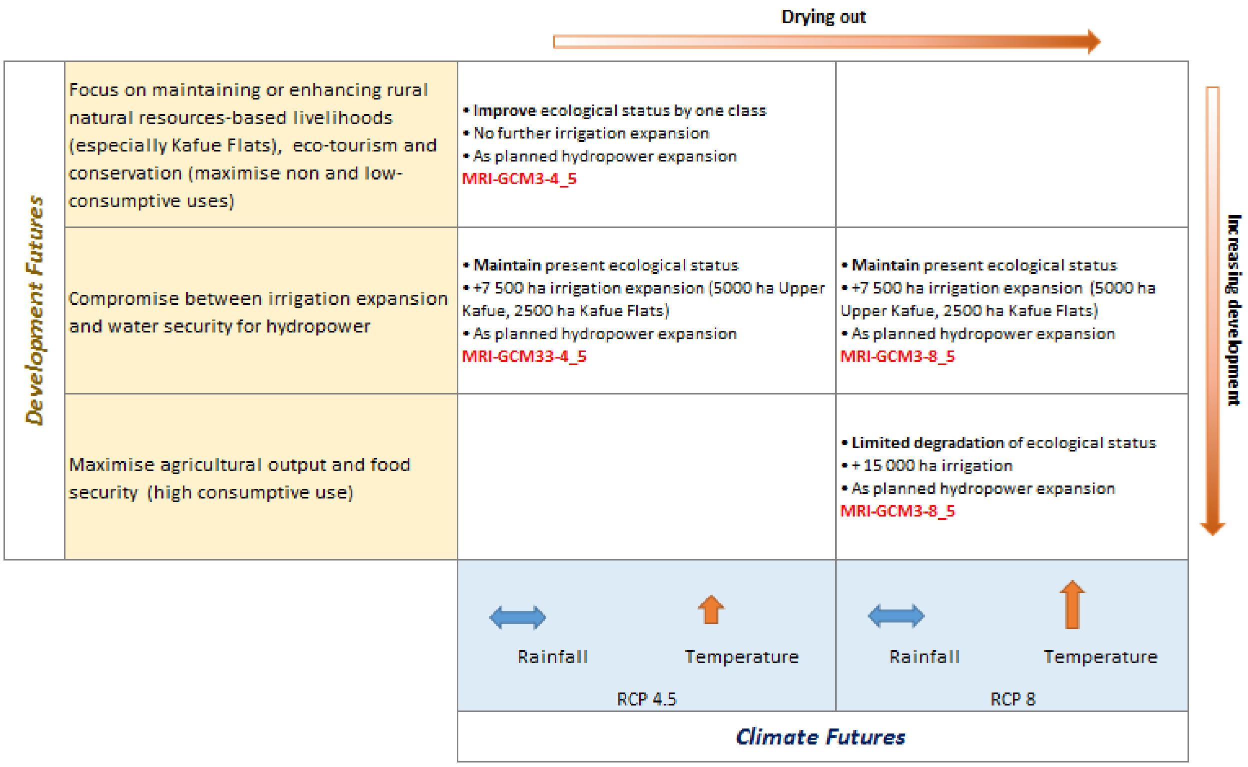

Source: CSAG/FRACTAL, 2018

higher temperatures and lower rainfall in the region. Temperatures are predicted to rise by 1°C or 1.5°C, as well as a prediction of varied seasonality (Ministry of Finance, 2013).

Alterations of the natural water cycle are expected, which will be exhibited by increasing severity of dry spells and short but intense rainfall events, which will cause an increase in flooding (see figure 4.4). The Climate Systems Advisory Group at the University of Cape Town in South Africa predicted three scenarios in Lusaka and the surrounding region. Lusaka is expected to receive reduced rainfall but more frequent extreme weather events by 2100 (see figure 4.5) . The first scenario is of a hotter and drier climate resulting in more severe droughts. The second predicts more extreme and erratic rainfall, resulting in a higher contrast between wet and dry seasons. The third foresees warmer temperatures and more extreme rainfall events. Regarding water supply, the second and third scenarios can bolster the groundwater supply if recharge zones are undisturbed.

Climatic baseline assessments undertaken over a 30-year period from 1970 to 2000 in the three main agroecological regions of Zambia revealed that there was a general trend showing decreased precipitation and increased episodes of precipitation below the 30-year average in all the regions (see figure 4.6).

Figure 4.6: Water Resources Development Scenarios




Source: Beekman, 2016

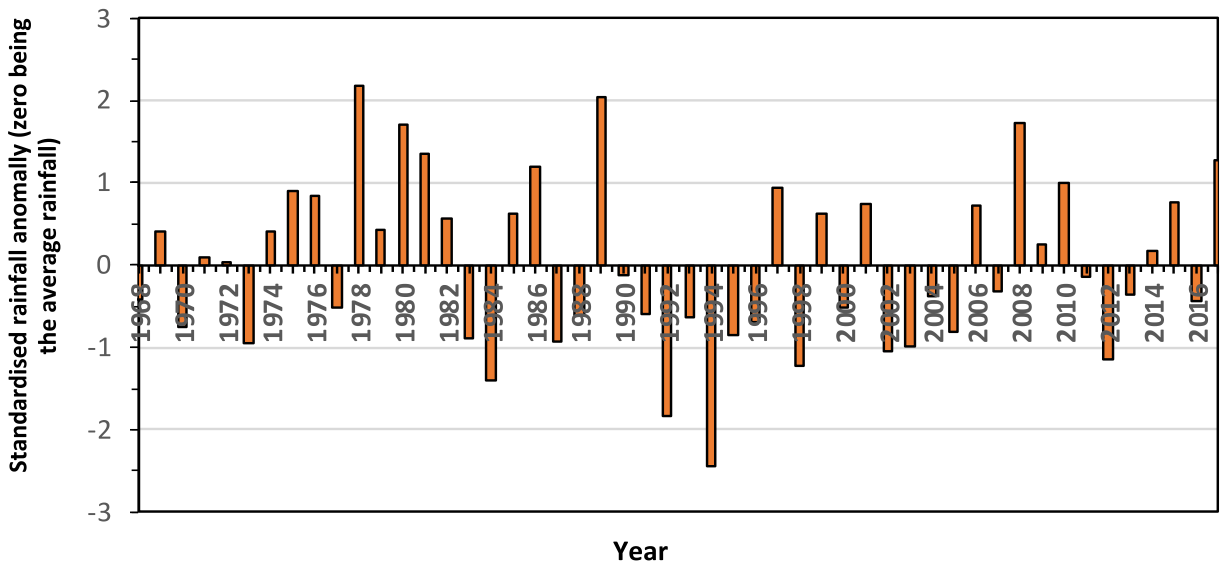
While developing the National Adaption Plan of Action, the Ministry of Tourism, Environment and Natural Resources in 2007 carried out studies which predicted climatic changes in Zambia, showing increasing mean temperatures for the period 2010–2070 averaging about 2˚C (MTENR 2007, 2010). The studies further indicate that increased temperature will result in reduced precipitation in the range of 8–30 per cent of the normal average. Episodes of drought are also projected to increase (Libanda and Ngonga, 2018).

### 4.2.4. Hydrological basin rainfall

The city receives most of its rain between December and February, with a monthly average of 200 mm. Historical rainfall figures show that rainfall in Lusaka and in Zambia as a whole has reduced. Figure 4.7 shows the rainfall deviations from the normal from 1968 to 2017. It indicates positive values when rainfall is above average and negative values for below average rainfall. The wettest years in Lusaka during the period were 1978, 1980, 1981, 1986, 1989, 2008, 2010 and 2017. Chisola and Kuraz (2016) show that the decline is statistically insignificant despite the general rainfall pattern showing a decrease in figures. The amount of run-off generated, on the other hand, shows an upward trend. This movement is due to an increase in impervious surfaces put in place in the built-up areas.

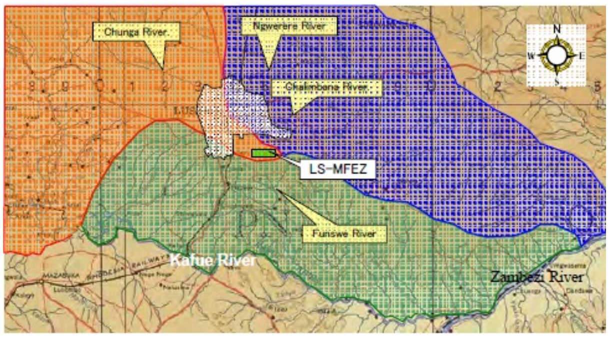
The city sits atop the Lusaka Plateau about 1,250–1,300 m above sea level. The plateau is one of the highest places within Lusaka District, and slopes gently from the south-east to the north-west. Lusaka city lies within the Chunga River Catchment Area (see figure 4.8). In the north-eastern part of the city, the Ngwerere and Chalimbana streams drain into the Chongwe River, a Zambezi River tributary (JICA, 2009). A series of small streams (Muchito, Funswe River) drain to the south of the city. Lusaka, however, relies on the Kafue River basin for part of its water supply and agricultural production. The river catchment is vital to the Zambian economy as it supports agriculture (irrigation, aquaculture), mining, industries, commerce, hydropower generation (at Itezhi tezhi and Kafue Gorge) and recreation. The Kafue River has so many competing demands, hence the need to ensure that the river basin remains healthy. The Kafue River, which starts in Copperbelt Province, is divided into

Figure 4.7: Standardized rainfall anomalies for Lusaka, 1967–2017



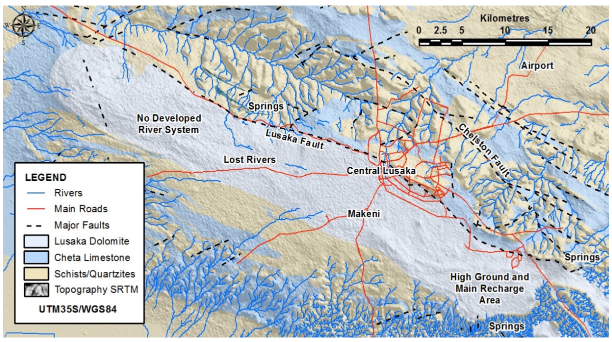

Source: Nchito et al, 2018

Figure 4.8: River catchments in Lusaka city region




Source: JICA, 2009

Figure 4.9: Aquifers and streams, Lusaka Region




Source: Karen et al, 2019

six hydrological zones. The city abstracts surface water from a point within Hydrological Zone 6. In the upper northern extents, the river is characterized by higher-yielding subcatchments (Beekman, 2016).

### 4.2.5. Water supply sources: Dams and aquifer levels

When Lusaka was a small railway siding, residents relied on surface water from the Ngwerere Stream. This was no longer feasible once the population increased, so groundwater sources were sought (Williams, 1986). The source was chosen despite Lusaka's location on a watershed at the centre of a radial drainage pattern made up of several small streams. Studies of aquifer patterns show that they have changed significantly. There are several aquifers in and around the city with varied recharge rates. Figure 4.9 shows the principal aquifer that lies in the Lusaka dolomite running from north-west to south-east. It also shows the cheta limestone on its edges in some places. These are highly productive carbonite aquifers (ADB, 2015).

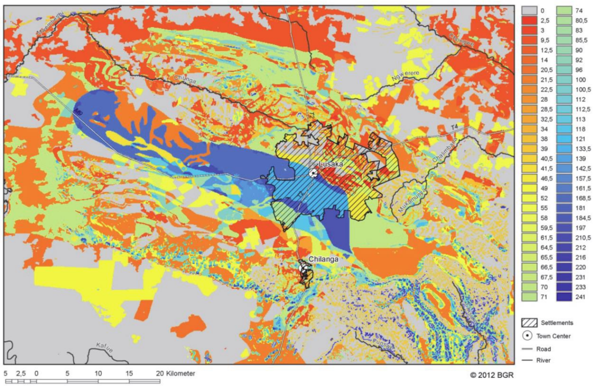
Lusaka City Council was originally the sole provider of water and waste management services until changes were made in the water sector in the 1990s. The city relies heavily on boreholes (see figure 4.10) for water since only 40 per cent comes from the Kafue River, 65 km to the south. The fast pace of urban expansion has caused numerous problems, among them waste management; evidence of this is the piles of rubbish dotted around parts of the city.

Table 4.3: Estimation water use in Lusaka according to category

| | Category | Amount of water (Mm³/a) |
|---|---|---|
| 1 | Public water supply | 50.0 |
| 2 | Private abstractions | 19.6 |
| 3 | Agriculture | 16.8 |
| 4 | Industry | 4.4 |
| | Total | 90.8 |

Source: Beekman, 2016

Figure 4.11: Groundwater recharge rates[mm/year] in Lusaka Region in a dry year 1983/84 (SN 4)




Source: Beekman, 2016

Lusaka is predominantly located on karstified marbles and dolomites with thin layers of topsoil, making most areas in the city prone to flooding (Karen et al, 2019). However, the underlying rock formations are highly porous, allowing water to seep into aquifers (see figure 4.10).

Water levels in the Kafue River have been declining. It is predicted that unless there is intervention, the trend will continue due to increased activities upstream (Beekman, 2016). The Iolanda Water Treatment Plant that services Lusaka city was commissioned in 1970 and expanded in 1978. The idea was to provide relief for the groundwater sources. Surface water supplies account for 40 per cent of the water used in Lusaka. However, abstraction from the Kafue has not caused any significant reduction to flows to date (Beekman, 2016).

The Lusaka dolomite is covered by an epikarstic zone of 5 metres depth on average, which can reach a maximum of 25 metres below the surface. Studies have shown that this epikarstic layer influences the distribution and amount of groundwater recharge. The transient state groundwater flow model of Lusaka and the wider region, between 1976 and 2035, covering 2,270 km², reveals that the current abstraction rates are below the natural recharge rate. This outlook implies that the aquifer can sustain the city if abstraction rates do not change.

The modelling used data from groundwater levels from 2009 to 2011 taken from 47 monitoring boreholes. There is currently no data for abstraction at a local microscale available due to the absence of detailed hydrological information (Beekman, 2016). The recent drying up and contamination of boreholes, the leading source of water supply, is a worrying trend in the city. Estimates of the abstraction rate are 90 million cubic metres/annum (Mm³/a). Users are in the categories shown in table 4.3.

The aquifer recharge rates are around 20–25 per cent of annual rainfall, which averages 180 mm/year. Figure 4.11 indicates the recharge during a dry year. Considering that the projections for Lusaka are drier and longer hot seasons, this may become a permanent scenario. Beekman (2016) notes that rainfall, groundwater level fluctuations and groundwater abstractions need monitoring for decisions concerning sustainable abstraction to be made.

### 4.2.6. Provision of water and sanitation in Lusaka

Years of inadequate expansion of water infrastructure and its maintenance characterized the early years of such services by local authorities. This neglect led to a drastic shortfall in water supply. The revenues for water and sanitation services were also stagnant for a long time, with many residents paying fixed amounts that were not reflective of the actual cost of service provision. This curtailed investment in the sector by local authorities. Default on payments for water were rampant as the resource was largely perceived as a common good to be provided without charge. Metering was poor, and leakages were prevalent in most residential areas. The water reforms implemented in the late 1990s into the early 2000s introduced commercial utilities in order to curtail some of these problems and ensure adequate water supply to cities.

The city's settlement pattern tends to be radial. The original city planning used zones with three main classifications of residential areas, low, medium and high income. The city, historically, had a distinct Central Business District (CBD), light industrial and heavy industrial zones. It had a large number of unplanned settlements that also had their origins in the colonial era. Currently, the city has 37 unplanned settlements within and around it (Lusaka City Council, 2005). Despite the term "peri-urban" being used to describe these settlements, many are close to the CBD and other medium and high-cost residential areas. Others on the periphery are on former agricultural or derelict land unsuitable for habitation due to poor drainage. Since 2000, there has been an increase in demand for residential land. As a result the city has continued to sprawl in all directions as people have constructed homes on unserviced land sold to them either by farmers subdividing their land or the local authority opening up new areas.

Although statistics are not available, it is known that the numerous commuters from different parts of the region increase the city's daytime population. The many car wash outlets dotting the city over the past 10 years have increased pressure on water resources and provided a possible new source of groundwater contamination. Another area of water demand is the numerous homes being built. This activity is exacerbated by the reduction in the surface area of land where rain can naturally seep into the aquifer.

Zambia's 11 commercial water utilities operate with relatively high levels of hidden costs due to inefficiencies. First, most utilities can only recover about two thirds of their total service provision cost. This outlook takes into consideration full capital costs. Second, utilities only manage to collect about 70 per cent of the revenues owed to them by their customers. Third, it is estimated that about 45 per cent of water produced by commercial utilities is lost in the distribution process due to technical and non-technical factors. This loss is referred to as non-revenue water (NRW). In other words, it is water for which no revenue is collected.

**Table 4.4: Increased supply through projects**

| | PROJECT AREA | OUTPUT | IMPACT |
|---|---|---|---|
| 1. | Mtendere/Kamanga- Water & Sewer Reticulation | 74.6 km of pipes for water supply network (Mtendere 60.2 km, Kamanga 14.4 km). | 155 000 people<br><br>6 400 (Mtendere) and 1 000 (Kamanga) house connections |
| 2. | Bauleni Water Supply Project | 5 km water distribution network and 108 m³ reservoir tank | 20 000 people |
| 3. | Chainda Water Supply Project | 4 km water distribution network and<br><br>108 m³ reservoir tank | 450 house connections |
| 4. | Woodlands Extension (Low density) | 12.4 km water distribution network | 422 house connections |
| 5. | Misisi Water Project | 7.07 km water distribution network | 100 house connections<br><br>20 Sheltered Kiosks<br><br>15 Open Kiosks<br><br>14 Communal taps rehabilitated. |
| 6. | Kalingalinga/Sanmark Project | 5.6 water distribution network | 150 house connections |
| 7. | Kabanana Water Supply Project | 2 km water distribution network and<br><br>Rehabilitation of Kabanana Tank | Improved water supply to 22 000 people |

Source: LWSC, 2023

### 4.2.7. On-site water supply and sanitation

The self-supply of water by residents is a major challenge in the city. Self-supply is when residents source water from where it can be found (Grönwall et al, 2010). In Lusaka, water is easily accessed from the aquifers where the water table is as close as 2–5 metres from the surface (Grönwall et al., 2010). In poorer neighbourhoods, this is mainly done through shallow wells dug within the yard. Unfortunately, in more affluent areas self-supply is in the form of boreholes. Self-supply water services go hand in hand with on-site sanitation. Self-service sanitation has caused a great risk of groundwater contamination in the city as unimproved pit latrines have been the main mode of sanitation for 95 per cent of the population living in unplanned settlements, while septic tanks and soakaways have been used in the more affluent areas (Water and Sanitation for the Urban Poor, 2018). The construction of most of these amenities is not monitored or certified as fit for use by the local authority. Unlined pit latrines and faulty septic tanks contaminate groundwater around the city, with unplanned areas like Kanyama and George Compound ("*compound*" is a parochial term used to refer to unplanned settlements in Zambia) being the most susceptible (ADB, 2015; Karen et al., 2019). The local authority has tried to reduce the reliance on shallow wells by banning them.

The use of eco-san toilets as well as the construction of improved pit latrines, which are lined, have been encouraged to reduce the risks of groundwater pollution in poorer areas. There is generally a rise in projects promoting the use of alternative sanitation solutions. An example is the construction of 60 dry toilets in Matero (Lusaka Times, 2022).

At the same time, the Lusaka Water and Supply Sanitation Company has increased the coverage of communal supply of water through public standpipes, or individual household taps through the Devolution Trust Fund (DTF) funding portfolio. Water Trusts, which are community-based schemes, also supply treated water from localized boreholes managed by the community. There have been several projects carried out around the city since 2015 to improve the water supply. These have been undertaken mostly in unplanned high-density informal areas where the supply and connectivity have lagged. Table 4.4 indicates the main projects completed and the expected number of beneficiaries.

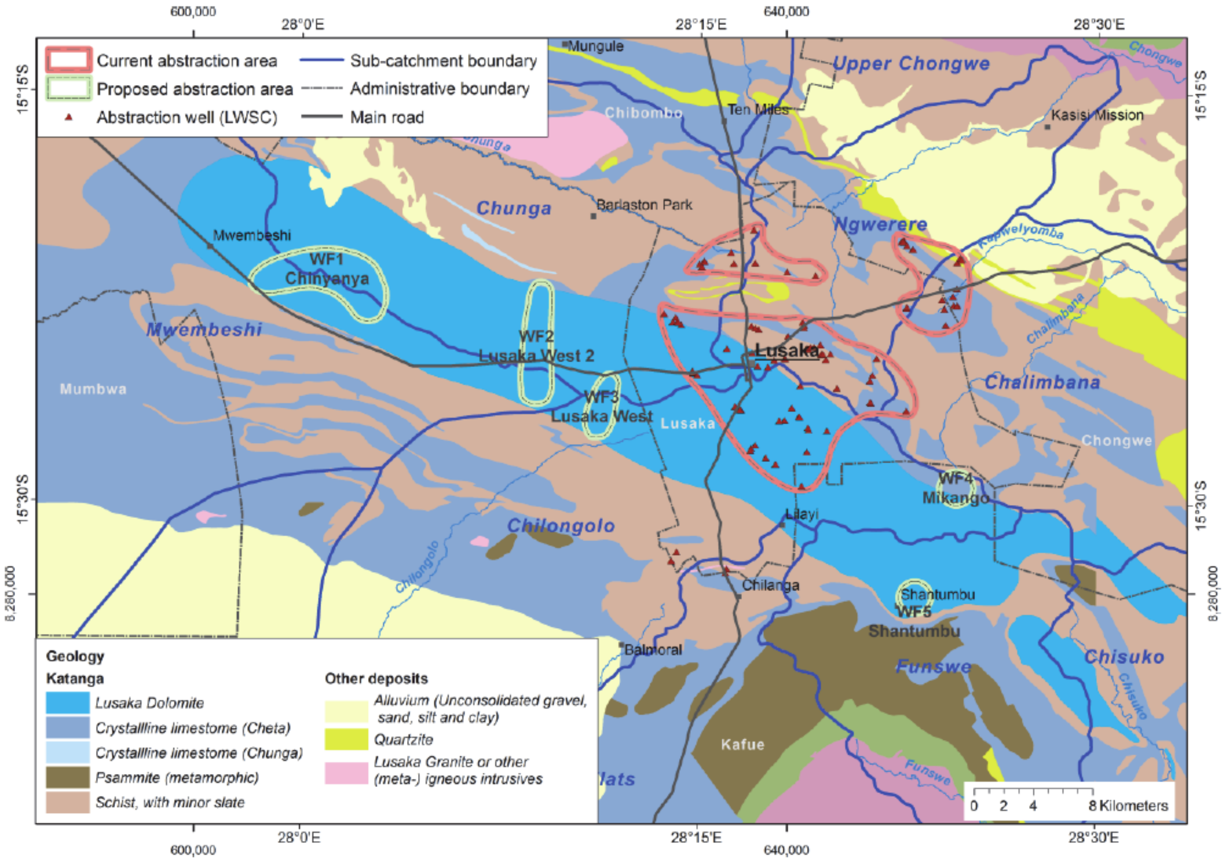
The level of contamination of groundwater is usually unknown until an outbreak of disease such as cholera. Lusaka had its last major cholera outbreak during the 2017–2018 rain season, leading to a rethink of the sanitation situation in unplanned settlements. A very small number of shallow wells can still be found in George Compound and a few other unplanned settlements in Lusaka. Outbreaks of cholera in Zambia have been frequent since 1990, and have become endemic. Notable outbreaks occurred in the years 1991, 1993, 1999, 2004, 2009, 2010, 2016, and 2017 with the total number of recorded deaths reaching 4,731 (Sladoje, 2018).

A very small number of shallow wells can still be found in George Compound and a few other unplanned settlements in Lusaka. There are no confirmed figures for the number of shallow wells in the city but an estimated 2 per cent of households still use such wells. A 2017 study by Water and Sanitation for the Urban Poor (WSUP) found that in some areas of the city, such as Kanyama settlement, about 40 per cent of the population use shallow wells for drinking water (Water Journalist Africa, 2017). The number of shallow wells fluctuates as there are serious efforts to eliminate them.

The use of eco-san toilets as well as the construction of improved, lined pit latrines has been encouraged to reduce the risks of groundwater pollution in poorer areas. There is generally a rise in projects promoting the use of alternative sanitation solutions. Potential abstraction sites for Lusaka Water and Supply Sanitation Company boreholes have been identified. These have a reduced risk of contamination (see figure 4.12).

In the more affluent areas, apart from the risks of contamination, there are risks of over-abstraction, and dry boreholes are becoming a prevalent feature in these areas. The exact quantities of water being drawn by private boreholes from various aquifers around the city remain unknown. Incidences of dry boreholes during the extended dry periods are indicative of over-abstraction and insufficient recharge. Hydrological mapping of the extent and geometry of the aquifers in Lusaka was carried out by the Federal Institute for Geoscience and Natural Resources, Germany, (Ministry for Energy and Water Development, 2009; Beekman, 2016). Modelling of water demand showed that if water abstraction increases near current wellfields, there could be a drop in water tables. For instance, it is projected that if water demand were to double by the year 2035, groundwater reserves would be insufficient (Beekman, 2016).

Figure 4.12: Current abstraction areas and potential new sites for groundwater exploitation - for Lusaka Plateau




Source: Beekman 2016

## 4.2.8. Water supply and demand

The current supply from the water utility is 225,000 cubic metres per day (this includes non-revenue water, meaning that the actual amount supplied is less) while the demand (including NRW) is 720,000 cubic metres per day. These estimates of demand are for Greater Lusaka, which includes other districts (see table 4.5). The large disparity is met by self-supply through the drilling of boreholes. The Lusaka Water and Sanitation Company embarked on the rehabilitation of the Iolanda Bulk Water Treatment Plant and Booster Station based on the Kafue River in 2015. This was funded by the United States Government at a sum of USD 45 million under the Millennium Challenge Account project. Previous rehabilitation had taken place in 1988 and in 2010. The project also aimed at reducing non-revenue water, rehabilitation of the transmission mains, expansion of water distribution networks, expansion of the water network, sewerage pump station upgrades, and upgrades to the Kaunda Square sewerage ponds. as providing technical aid.

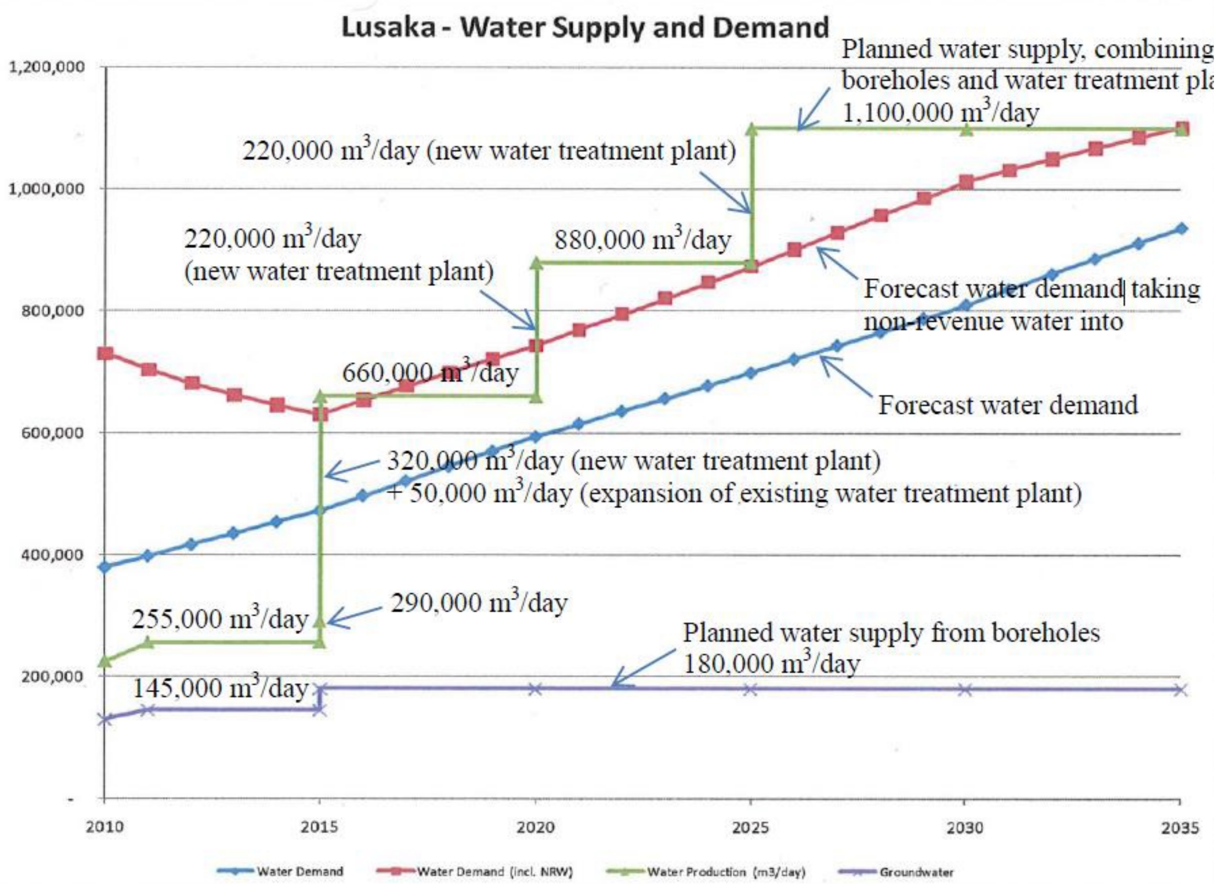
There is a USD 150 million additional plant being constructed on the Kafue. The plant has been completed and is being tested, though a separate substation is required. The plant has a capacity of up to 150,000 m³/day but will only be able to produce 50,000m³/day under the current configuration. The plant was completed and commissioned in July 2022 and consists of a new treatment station and a booster station at Chilanga which also has a booster for the old system. The current works are in light of the expected increases in demand (see figure 4.13).

**Table 4.5: Population projections and water demand (Greater Lusaka)**

| | | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|---|
| **POPULATION** | | | | | | | |
| LUSAKA DISTRICT | AAGR 2,82% | 1,742,979 | 2,213,962 | 2,812,208 | 3,260,112 | 3,779,367 | 4,381,324 |
| Kafue | | 42,071 | 50,000 | 100,000 | 137,840 | 190,000 | 261,897 |
| Chongwe | | 26,740 | 50,000 | 100,000 | 126,491 | 160,000 | 202,386 |
| Chibombo | | 17,788 | 30,000 | 30,000 | 45,826 | 70,000 | 106,927 |
| GREATER LUSAKA POPULATION | | 1,830,000 | 2,340,000 | 3,040,000 | 3,570,000 | 4,200,000 | 4,950,000 |
| **DEMAND** | | | | | | | |
| DEMAND (m3/d) | | 379,552 | 472,463 | 594,155 | 698,788 | 810,359 | 936,896 |
| DEMAND (m3/d) incl. NRW | | 730,100 | 629,951 | 742,694 | 873,485 | 1,012,949 | 1,102,231 |

Source: MCA 2011
NB: Annual average growth rate

Figure 4.13: Projected water demand and water supply for Lusaka (2010–2035)




Source: Beekman, 2016

## 4.3. ACTIONS TAKEN

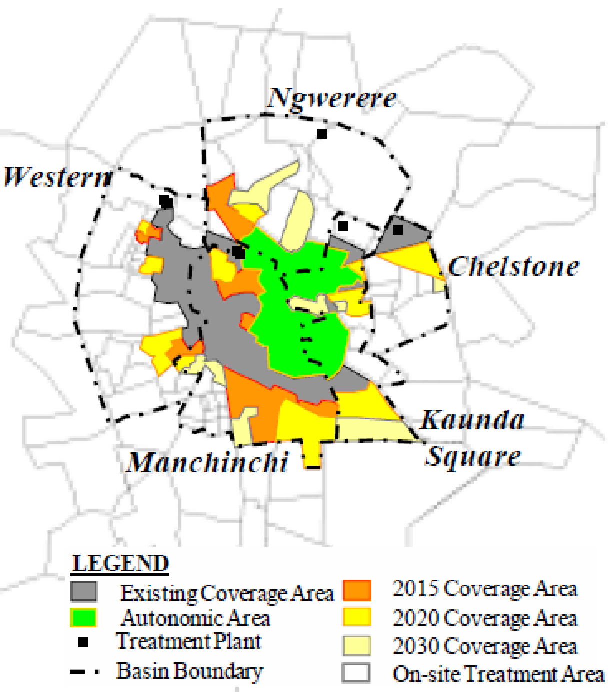
### 4.3.1. The practice

For many years, investments in the water sector have lagged behind human population growth and water demand. The original system was designed for 200,000 people but currently the city has over 2.3 million inhabitants and over 100 industries.

The implementation of water supply projects has been embarked upon by the company in order to bridge the supply-demand gap shown in table 4.5. Projects such as the Kafue Bulk Water Supply, which will provide an additional 50,000 m³/day, and the rehabilitation of the Iolanda Treatment Plant under the Lusaka Water Supply Drainage project financed by the Challenge Account have increased the number of city households supplied with water. However, there are other projects which are at feasibility stage and water supply improvement projects in peri-urban areas that are yet to be funded. The Lusaka West Wellfield is one such project meant to serve residents within this area but more importantly and economically significant, the industries in the Western part of the city.

As mentioned for the water supply system, a sewerage master plan also needs to be prepared so that future works can be fully planned, reflecting the water supply design of the city and for the protection of groundwater resources. The JICA-funded master plan up to 2035 for Lusaka includes sewerage services but only recommends the rehabilitation of existing facilities and expansion of the sewer line (JICA, 2009; see figure 4.14). The African Development Bank funded the five-year Lusaka Sanitation Programme, launched in 2017, to overcome this challenge.

Figure 4.14: Sewerage services development scenario




Source: MLGH, 2009

In terms of sewage treatment facilities, Lusaka has two conventional treatment plants and five non-conventional ones in the form of wastewater stabilization ponds. These conventional plants are the Chunga and the Manchinchi and the non-conventional ones are the Garden, Matero, Ngwerere, Kaunda Square and the Chelstone stabilization ponds (see figure 4.15 and table 4.6). The conventional plants comprise screening and grit removal facilities, primary sedimentation tanks, biological filters, final sedimentation tanks, maturation ponds, and sludge treatment facilities. All the treatment facilities serving Lusaka are hydraulically overloaded, with around twice the maximum design flow. Overloading is obvious at the Manchichi Wastewater Treatment Plant, where the storm overflow weir is in continuous operation with excess flow directed to maturation ponds. This is causing further problems at the ponds, as they were not designed to accept raw sewage. According to the Sanitation Master Plan of Lusaka (2011), the LWSC network covers approximately 30 per cent of the city area, and it is accessible to 10–20 per cent of the residents. Lusaka is divided into five sewer sheds; table 4.6 shows the extent of the area covered by the various plants.

Between 10 per cent and 15 per cent of the population is served by waterborne sewerage (ADB, 2015). There is no database for septic tanks and hence no absolute figures for residents who use them. The same applies to pit latrines. It is assumed that unplanned settlements predominantly use pit latrines.

#### 4.3.1.1 Community-managed water trusts

In order to augment the efforts of the Lusaka Water and Sewerage Company, particularly in the provision of water to peri-urban areas, water trusts were formed as community-based organizations. The trusts were tasked with providing water in the unplanned settlements under the general licence of the Lusaka Water and Sewerage Company. This measure has helped to formalize the supply of water.

In 1992, the central Government asked CARE International to set up water trusts as a mitigation measure against

### Table 4.6: Summary of LWSC sewer shed areas

| S. No. | Sewer shed Area | Coverage (in ha.) | End Treatment Units | Size of Sewer Main (in mm) |
|---|---|---|---|---|
| 1. | Matero/Chunga | 930 | Chunga Treatment Plant and Matero Ponds | 150–750 |
| 2. | Manchinchi | 1 860 | Manchinchi Treatment Plant | 50–900 |
| 3. | Kaunda Square | 1 570 | Kaunda Square Ponds | 50–750 |
| 4. | Chelston | 260 | Chelston Ponds | 150–225 |
| 5. | Ngwerere | 770 | Ngwerere Ponds | 150–900 |

Source: Sanitation Master Plan, Lusaka, Zambia (2011)

### Table 4.7: Water trusts, supply and populations served

| POPULATION SERVED IN WATER TRUSTS | | | | | | | |
|---|---|---|---|---|---|---|---|
| District | Number of Kiosks | Approximate number of beneficiary households | No. of People per Household | Individual connections | Estimate of Population Served from individual connections | Estimate of Population Served from kiosks | Total Estimate of Population Served |
| WATER TRUSTS AREAS | | | | | | | |
| EASTERN ZONE | | | | | | | |
| NG'OMBE | 89 | 3 | 10 | 1,250 | 12,500 | 2,670 | 15170 |
| KALIKILIKI | 26 | 3 | 10 | 428 | 4,280 | 780 | 5060 |
| GARDEN | 62 | 6 | 10 | 1,400 | 14,000 | 3,720 | 17720 |
| MTENDERE EAST | 24 | 6 | 10 | 1,760 | 17,600 | 1,440 | 19040 |
| | **201** | **18** | **40** | **4,838** | **193,520** | **144,720** | **338,240** |
| SOUTHERN ZONE | | | | | | | |
| CHIBOLYA | 44 | 6 | 10 | 1,037 | 10,370 | 2,640 | 13,010 |
| KANYAMA | 137 | 17 | 10 | 5,600 | 56,000 | 23,290 | 79,290 |
| FREEDOM | 22 | 6 | 10 | 363 | 3,630 | 1,320 | 4,950 |
| | **203** | **29** | **30** | **7,000** | **210,000** | **176,610** | **386,610** |
| WESTERN ZONE | | | | | | | |
| CHAZANGA | 56 | 8 | 10 | 4,100 | 4,480 | 41,000 | 45,480 |
| CHIPATA | 67 | 4 | 6 | 3,249 | 1,608 | 19,494 | 21,102 |
| CHAISA | 69 | 4 | 6 | 430 | 1,656 | 2,580 | 4,236 |
| | **192** | **16** | **22** | **7,779** | **67,584** | **171,138** | **238,722** |
| | | | | | | | |
| **Grand Totals** | **596** | **63** | **92** | **19,617** | **471,104** | **492,468** | **963,572** |

Source: NWASCO, 2020

drought and the effects of the International Monetary Fund's Structural Adjustment Programmes. Six trusts were created initially. The model was replicated and 12 trusts were located in Lusaka's unplanned settlements. Established trusts received oversight from the Lusaka Water and Sanitation Company through a Delegated Management Contract arrangement. Water trusts' key collaborating partners include Lusaka City Council, the local authority; Lusaka Water and Sanitation Company, the mandated water and sanitation service provider; the Ministry of Community Development, Mother and Child Health, the line ministry on issues of equity and vulnerability; plus the ward-based development committees that provide community leadership (Nkonkomalimba and Mumba 2014). Currently, there are 11 water trusts in Lusaka, from the original 12, supplying about 40 per cent of the population accessing water in Lusaka (see table 4.7).

#### 4.3.1.2 Formation of a multi-stakeholder platform

The Lusaka Water Security Initiative (LuWSI) is a multi-stakeholder initiative that began in 2016 with 16 partners, initially funded and hosted by GIZ . It aims at improving water security for residents and businesses in Lusaka. The initiative now has 30 partners from the private and public sectors and civil society. LuWSI was established with the recognition that there was a need to improve multi-stakeholder collaboration, improve access to information, and improve understanding of water risks and threats. LuWSI's mission is "to strengthen multi-stakeholder collaboration to safeguard Lusaka's water resources, while enhancing sustainable and timely access to water and sanitation for all". LuWSI's partners are currently collaborating on projects aimed at ensuring the sustainability of water supply in the city.

#### 4.3.1.3 Implementation of projects by Lusaka Water Supply and Sewerage Company

The Lusaka Water Supply and Sewerage Company (LWSC) has tried to improve water supply in Lusaka city over the past 10 years. Table 4.8 highlights the key projects the utility has undertaken. The augmentation of water treatment capacity is done by expanding the existing treatment plants to avoid increasing the number of facilities that require management. The Iolanda Water Treatment Plant is, however, faced with a problem as it is 10 kilometres downstream of industries in Kafue town. The decline of industries in Kafue may reduce this threat currently, but in the event that the trend is reversed, the contamination of the raw water may increase, and the operations at Iolanda will eventually have to be revisited. The wastewater treatment plant in Kafue will need to be

Figure 4.15: Ngwerere treatment ponds

Source: Millennium Compact, 2017

managed by Kafue District Council and Lusaka Water Supply and Sanitation Company since the river is a shared resource. The management of sewage ponds is also not consistent, and the effluent is eventually released into the river.

### 4.3.2. The spatial dimensions

The extent of the water problem is large and is quickly expanding as the city grows. Climate hange will worsen the problem. The lack of adherence to planning regulations has created a huge challenge. The spatial dimensions of the problems are as a result of: the high number of unplanned settlements that for a long time were ignored and considered illegal and not included in the provision of services; the increase of new unserviced areas is being opened up on the city's fringes since most occupy former farmlands that require utility services; and a strained commercial utility in terms of funding and financing for major projects.

#### 4.3.2.1 Informal settlements

Lusaka has a long history of unplanned settlements that are often referred to as peri-urban areas, even though not all are in the city's peri-urban region. In total, the city has 37 unplanned settlements, which provide accommodation for about 70 per cent of the population even though they only cover 20 per cent of the city's total area. This is an indication of the high populations found in informal areas of the city that do not have adequate provisions of water and sanitation services.

Water supply modalities in unplanned settlements are dualistic in that there are either formal or informal types of supply. The formal service modality is viewed as

**Table 4.8: Lusaka Water Supply and Sewerage Company projects**

| LIST OF PROJECTS | PROJECT COST | FUNDING AGENCY | STATUS | NUMBER OF BENEFICIARIES |
|---|---|---|---|---|
| Lusaka Water Supply, Sanitation and Drainage Project (2014–2022) | USD 354 M | (MCC) | 98.4% | 1 240 000 |
| Kafue Bulk Water Project (2016–2019) | USD 150 M | GRZ/Chinese Government | In progress (99%) | 480 000 |
| Construction of 3no. Boreholes in Kabanana, Nyumba Yanga & Tiyende Pamodzi (2013) | ZMW 1.55 M (USD 300,000) | GRZ | Completed | 12 000 |
| Construction of water distribution networks at Farms 917 and 1080 (19.3km) in Kamwala South | ZMW 6.576 M (USD 1.30 M) | LWSC (Commercial loan from ZANACO) | Completed (2013) | 4 000 |
| Supply, installation and commissioning of 420m3 Steel Tank in Hillview area of Lusaka | ZMW3,084,017.19 (USD 760,000) | LWSC | Completed | 26 000 |
| Linda Water Supply and Sanitation Improvement Project (2013) | ZMW 2,817,360 (USD 650,000) | European Union/LWSC | Completed | 20 000 |
| Manzi Ndi Umoyo Rain Project (Bauleni & Chainda) 2013 | ZMW 3.1 M (USD 600,000) | The Coca-Cola Family Foundation | Completed | 63 000 |
| Kabanana Water Supply Project (2015) | ZMW 1.8 M (USD 360,000) | DTF-funded Project | Completed | 22 000 |
| Misisi Water Project (2015) | ZMW 2 M (USD 400,000) | DFID and Wasser fur Wasser | Completed | 30 000 |
| Construction of water distribution networks at South of Hillview | ZMW 7.94 M (USD 1.58) | LWSC (Commercial loan from ZANACO) | Completed | 14 000 |
| Chunga tank replacement (2017) | ZMW 1.184 M (USD 295,000) | LWSC | Completed | 4 000 |
| Construction of 3,200m water network and 20 water kiosks in John Laing Phase 2 (2012) | ZMW 1.7 M (USD 340,000) | LWSC/DTF | Completed | 32 000 |
| Emergency works on peri-urban areas. Drilling of boreholes, construction of reservoir tanks and water distribution networks in 6 peri-urban areas 2020–2021 | ZMW 153 M (USD 7.65 M) | GRZ | In progress | 95 000 |

legal. Single household connections are mostly found in medium- and high-income neighbourhoods. These are also found in unplanned settlements, but in small numbers. The other is an informal service modality, which comes in the form of kiosks, standpipes or mobile water vending. There are also some modalities that contain elements of both (Ahlers et al. 2014). Residents pay for water as they collect it from the kiosks or standpipes. The advantages of this method of communal water supply are that residents are assured of receiving treated water, reducing the incidence of waterborne diseases. It also reduces the wastage of water as residents ensure that they efficiently utilize what they collect.

#### 4.3.2.2 Urban sprawl

The city was originally contained within a central zone, and outward expansion was minimal. The increase in migrants from the declining Copperbelt and the continued concentration of economic activities in the capital have led to a rise in demand for housing. The sale of institutional housing and the housing deficit have also led to a homeownership drive, which has increased the pressure on existing land. The urban fringe, which was dominated by commercial farming and market gardening activities, has now changed use and is predominantly residential. The rapid rate of expansion has meant that the commercial utility has not been able to keep up with the demand. The planning authorities have authorized new areas and changes of use without ensuring that the new areas are first serviced. This has created a situation where homeowners self-supply water and sanitation services through the drilling of boreholes and the construction of septic tanks. This takes place in all the newly opened areas that surround the city. These are usually middle- to low-density areas and could be a source of revenue for the commercial utility, but the lack of coordination and financing have squandered this potential. The opportunity for smaller localized water supply systems managed by the commercial utility or privately has also been lost because WARMA regulations on boreholes have not been adequately enforced.

#### 4.3.2.3 Financially constrained commercial utility

The LWSC has had problems caused by insufficient investment levels, low rates of recovery, and high non-revenue water, which have kept it in a constrained position for investments. The entity also reports being "adversely affected by the volatility in the macroeconomic parameters such as exchange rates, and the resulting exchange loss associated with the World Bank dollar-denominated loan, inflation, and interest rates, as well as the below target water production" (LWSC, 2018:23).

The company has experienced fluctuations in revenue generated over the years due to the aforementioned causes. For instance, in 2015, the company generated ZMW 209.6 million (USD 39.9 million), down from ZMW 217.7 million (USD 41.5 million) generated in 2014. However, there was an increase in revenue in 2016, when the figure rose to ZMW 245.7 million (USD 46.8 million) and ZMW 279.3 million (USD 72.5 million) in 2017 (LWSC, 2018). This is an indication of the uncertainties faced by the commercial utility in terms of profitability, making it difficult for the Lusaka Water Supply and Sewerage Company to provide efficient services and expand the network.

The collection of revenue is another challenge for the commercial utility. Collection efficiency, which is defined as the total collections (inclusive of arrears) of the total billings, also showed a downward trend, with 88 per cent in 2014, 86 per cent in 2015, and 78 per cent in 2016 (LWSC, 2018). However, in 2017, at 86 per cent there was an increase in the collection efficiency. With the right support, the utility can become more financially sustainable.

### 4.3.3. Institutional and regulatory framework

Reforms in the water sector started in the early 1990s and are ongoing. The initial reforms were in line with the global restructuring that was taking place in the water sector. The reforms had three different formats (Chitonge, 2012). There were reforms in the management of water, in policy and legal frameworks, and finally institutionally.

Management reforms considered the mechanisms used in the delivery of water services. At the time, water was supplied by local authorities. After the reforms, departments responsible for supply were transformed into commercial utilities, which were registered as private entities owned by the local authority. The Lusaka City Council formed the Lusaka Water and Sewerage Company (now the Lusaka Water Supply and Sanitation Company) in 1989, which was the first commercial utility to be formed. It was later followed by the formation of 10 others nationwide. All assets that were formerly publicly owned were transformed into private assets managed by a limited company (Chitonge, 2012).

Policy and legal reforms encompassed the entire water sector, including services and resource management. The result was the National Water Policy of 1994, the Water Supply and Sanitation Act No. 28 of 1997, and eventually Water Resources Management Act (WARMA) Act No. 21 of 2011, and the Groundwater and Boreholes Regulations

**Table 4.9: Key sector outputs and progress**

| | SUBSECTORS | OUTPUTS AND PROGRESS MADE |
|---|---|---|
| 1. | Water Resources Development and Management | • Nation Water Policy (1994)<br>• Water Resources Action Programme (2002)<br>• Water Resources Management Bill (2006)<br>• Draft National Water Policy (2007)<br>• Draft IWRM Implementation Plan (2007)<br>• Water Supply and Sanitation Act (1997)<br>• Water Resources Management Act (WARMA) (2011)<br>• The Groundwater and Boreholes Regulations (2018) |
| 2. | Urban Water Supply and Sanitation | • National Water Supply and Sanitation Act in 1997<br>• Transfer of 46 water services schemes as well as the responsibility for rural water supply and sanitation from MEWD to local authorities under the supervision of MLGH (1997)<br>• Establishment of NWASCO in 2000<br>• Establishment of Department of Infrastructure Support Services in the MLGH to improve infrastructure investment<br>• Establishment of 10 commercial utilities for<br>• urban/peri-urban water supply and sanitation<br>• Operationalisation of the Devolution Trust Fund (DTF) for the facilitation of extending services to low-income urban areas (2002) |
| 3. | Rural Water Supply and Sanitation | • Establishment of a rural water supply and sanitation unit in the Department of Infrastructure Support Services in 2003<br>• Adoption of the Rural Water Supply and Sanitation Institutional and Financial Framework in 2004<br>• Development of National Rural Water Supply and<br>• Sanitation Programme, 2006 |

Source: GRZ, 2008; NWASCO, 2020

of 2018 Nos. 18, 19 and 20. The purpose of these laws was to create a national regulatory framework for the sector.

Under the institutional reforms, the National Water Supply and Sanitation Council (NWASCO) was set up to provide oversight for those dealing with water supply and sanitation. The agency's role is to regulate commercial utilities and other water supply and sanitation service providers. Under the policy, the Government considered peri-urban areas as legal settlements, which were to be served with water and sanitation facilities as were formal areas. This proclamation has caused an added strain on commercial utilities as they are required to provide water supply and sanitation services in the areas under their jurisdiction. The policy aimed at providing these services adequately, safely and cost-effectively with due regard to environmental protection.

These changes placed water under the Ministry of Energy and Water Development, now reconfigured under the Ministry of Water Development, Sanitation and Environmental Protection. The sector needed coherence for the efficient management, planning, and development of water resources (GRZ 1994, National Water Policy). The National Water Policy of 1994 predicted that the country would face severe shortages due to increased industrial and domestic demand for water. Pollution has been exacerbated this shortage. The implementation of the various policies has produced several positive outputs that have improved the water sector in the country as observed in the increase of water supply coverage from 2016 to 2020 (see table 4.9).

### 4.3.4. Technology

Technological developments have enabled the utility to connect households in formerly unserviced areas and install water points or kiosks in some areas. The water sources developed during this period are mainly boreholes spread across the city. Overall, the production from the boreholes accounts for about 60 per cent of the total water supplied to Lusaka. Drilling boreholes is a cheaper option for the utility to increase its production than to develop capital-intensive surface water treatment systems. However, as indicated earlier, the Government mobilized resources for the construction of a surface water treatment system under the project called the Kafue Bulk Water Supply, whose scope includes raw water intake on the Kafue River, a water treatment plant, and a 65-km pipeline from Kafue to Lusaka via a booster station at Chilanga District,  midway between the towns.

Lusaka is supplied with surface water (about 40 per cent) and groundwater about 60 per cent. The surface water goes through the conventional treatment plant of flocculation, sedimentation, filtration and disinfection before the water is supplied for domestic and industrial use. Groundwater, on the other hand, is abstracted from deep boreholes using electrical borehole pumps, goes through disinfection only and is pumped into overhead tanks and supplied through gravity to consumers. Most of the consumers in the high-, medium- and low-cost planned areas are supplied through individual connections while the peri-urban areas are mainly supplied using water kiosks as a quick intervention in providing quality water in the immediate term. About 62.2 per cent of the population in Lusaka is supplied with water through kiosks and standpipes. Water supply by the water trusts is mainly provided using satellite supply models (independent systems) though two of the water trusts, namely Ngombe and Chipata, are supplied from the Lusaka Water and Sanitation Company network.

### 4.3.5. Financial management and costs

In undertaking the action to improve water supply to Lusaka, the utility financed the various projects and activities in different ways (see table 4.6). The implementation costs were met in different ways including the utility's own funds, loans from commercial banks and international financing institutions as well as grants from international cooperating partners.

The funds under the various projects implemented were managed by a dedicated project team supported by an accountant with backing from the utility's Finance Division. This meant that separate project accounts were established and funds managed according to project requirements. This brought in efficiency in the management of the projects, which allowed the community utility to finish the projects on time. The main project costs included payments to consultants, contractors and compensation of project affected persons. The Lusaka Water and Sanitation Company is determined to improve its revenue collection. The entity has been bolstered by funding from international agencies, which have enabled it to expand and refurbish its infrastructure. The regulator, NWASCO, has also revised its tariff application guidelines to incorporate full cost recovery principle without passing on the inefficiencies to customers.

## 4.4. IMPACTS AND CONSTRAINTS

The projects under the action have enabled the utility to improve service delivery to the 85,000 customers that existed before the action and helped to increase the customer base to 115,000 by the end of 2019. This has resulted in increased revenue. Furthermore, it has contributed significantly to the country's vision 2030 for all to have access to safe potable water.

Despite the successes, there were numerous challenges faced during project implementation. These included difficulties in securing land for the project components, as was experienced on the main schemes such as the Kafue Bulk Water Supply Project as well as the Lusaka Water Supply, Sanitation and Drainage Project. This was worsened by delayed compensation payments to people affected by implementation of the project.

As a result of some of the interventions under the LWSC, namely the Millennium Challenge Account and the World Bank projects, the company has been able to increase production to 105,000m$^3$/day from 94,000m$^3$/day from Kafue Bulk Water Supply. Storage capacity has increased with more than six elevated reservoirs constructed. Water losses have been reduced, thereby making more of it available to other consumers. New areas have been supplied with water for 24 hours a day, for instance areas such as Kwamwena, Ndeke, Kamanga and Vorna Valley. The projects have also improved efficiencies of pumps at booster stations and helped in remodelling the pumping stations for efficiency.

## 4.5. SUSTAINABILITY AND REPLICABILITY

Within the global water sector, there are some critics of the over reliance on supply driven urban water provision. Critics say the high cost of capital investments in new treatment and distribution networks is often inappropriate, as some projects become white elephants (Vairavamoorthy, 2008). However, in developing countries like Zambia these large capital projects are still a necessity if water supply is to improve for citizens.

Lusaka Water and Sanitation Company is implementing asset management through a department that has been established and capacitated with technical support from the Millennium Challenge Corporation during the implementation of the Lusaka Water Supply, Sanitation and Drainage Project. The asset management team is working with all departments within the commercial utilities to ensure that operations and maintenance schedules of works are documented in order for the company to track the performance of installations. This enables the company to plan its repair or replacement of installations to guarantee sustainability of service provision.

Furthermore, the company attached its staff during the implementation of the projects under the action, thereby enhancing its capacity to implement most of the activities internally. This capacity developed and the financial benefit through increased revenues from a greater customer base is enough motivation for the utility to replicate the action in other areas. However, ensuring availability of land for projects and resources for compensation of people within the project sites and corridor are vital for repeating the action.

There have been noticeable incremental improvements to water and sanitation access in unplanned settlements which have been a result of the steady progress of the water management sector in Zambia over the last 20 years. Replication of the Water Trust Model has also led to improvements in service quality and affordability of water in unplanned settlements. The Trusts have allowed communities to formally supplement the services supplied by LWSC. Management of the Trusts is through service contracts. Whereas most Water Trusts focus on water delivery, some have included sanitation services. So far, Water Trusts in Kanyama and Chazanga also provide sanitation services. The Water Trust model has been successful in improving water supply in unplanned settlements and should be promoted nationwide as an alternative whilst Commercial Utilities are still struggling to reach 100 per cent coverage. Water Trusts have proved to be a replicable system of supplying unserved communities.

LuWSI's main contribution towards Lusaka's water security has been the creation of a multi-stakeholder platform on which public sector institutions like NWASCO, Lusaka City Council and WARMA and the University of Zambia, private entities and manufacturers such as Zambia breweries, Manzi Valley, Coca-Cola Zambia and Zambia Chamber of Commerce and Industry (ZACCI), and civil society can collaborate across different mandates and interests. The increased collaboration has resulted in the strengthening of organizational and personal relationships between actors which has allowed the identification of solutions to complex water security challenges. This approach to the management of city water can and should be replicated as it has enabled the speedy response to urgent problems as was seen during the COVID-19 pandemic.

In order to enhance sustainability, the company has implemented asset management plans and engaged a maintenance crew. The Lusaka Water Supply and Sewerage Company has also embarked on monitoring the impact of rehabilitation as opposed to maintenance and as a result an  asset maintenance system has been put in place.

## 4.6. OUTSTANDING ISSUES

Despite the improvements in water supply in Lusaka city, a number of activities will need to be undertaken to improve the service further. SomOne outstanding activities is commissioning of the Kafue bulk water supply, which is still outstanding due to the delay in the construction of a substation meant to supply electricity to the new plant. The substation's generation would reduce non-revenue water to acceptable levels and expand the network to support the increased water supply. Some areas like Chelstone on the eastern end of the city still need greater water supply to meet the demand. The new reservoir tank has been completed at Chelstone and is waiting to be filled from the Kafue Bulk Water Supply. Filters to support the increased capacity at Kafue are also still outstanding.

Extensions to the sewerage network have been minimal with most additional structures relying on septic tanks. The Zambian population is still far from accepting the use of recycled water. Water use practices remain entrenched in a mindset of surplus supply, but this needs to change considering the predictions of increasing dry spells and the steady rise in urban population.

## 4.7. RESULTS

### 4.7.1. Impacts of interventions

Implementation of the various projects under the action have increased access to safe potable water directly to 210,000 individuals through the new 30,000 household connections. Moreover, 300,000 individuals have received improved water supply to the existing kiosks and newly commissioned ones. Furthermore, the installation and commissioning of the elevated steel water tanks have contributed to improved hours of supply which could have been affected significantly by the introduction of power load management by the electricity supply company. LWSC has been able to supply water to customers in selected areas during periods of power load shedding through the installed elevated steel water tanks.

### 4.7.2. Strengths of the actions

The implementation of the Lusaka Water Supply, Sanitation and Drainage Project facilitated the installation of the backbone water network for the efficient distribution of water to the existing customers and future expansions. This initiative has enabled the utility to provide water to the Chelstone distribution centre, thereby improving quality to some sections of the neighbourhood, such as Avondale (a residential area next to Chelstone), and surrounding areas that were water stressed before the intervention.

The commissioning of the Kwamwena and Ndeke water distribution centres and water reticulation systems has provided 24-hour access to safe drinking water for more than 119,000 Lusaka residents (see figure 4.16). The operation of these facilities has also created the potential for LWSC to grow the customer base by an additional 14,000.

The commissioning of the Kafue Bulk Water Supply Project will significantly improve the production capacity by 50,000m$^3$/day, thereby facilitating the utility to improve water supply service quality, increase its customer base and, consequently, its revenue. These facilities will directly benefit more than 480,000 city residents.

Figure 4.16: Tanks built to improve water reticulation in Woodlands Extension, Lusaka

Source: LWSC, 2023

Self-supply has served to alleviate pressure from the Lusaka Water Supply and Sanitation Company. The ability of a large number of residents to access borehole water has allowed the utility to focus on less privileged communities. Despite the situation not being the most efficient use of water resources, it has enabled the city to continue functioning and being productive as the number of households with connections will be limited to households that will not have alternative sources.

### 4.7.3. Weaknesses of the action

The utility cannot mobilize resources to provide power supply to the new facilities constructed under the Kafue Bulk Water Supply Project. It completely depends on Government, which has committed to funding the construction of the substation for the new WTP through the Ministry of Local Government.

Despite the increase in customers due to the action taken, the utility has not provided 100 per cent metering. This situation makes it difficult to collect revenue in certain areas when customers dispute bills when supply is inconsistent.

Self-supply of water by boreholes is unsustainable, which is why there are now efforts to rationalize and regulate their use in the city. With climate change, a series of seasons with drought has the potential to cause extreme water stress.

### 4.7.4. Financial efficiency

All the projects under the action were implemented efficiently with minimal cost overruns and completed within the project timeframe (LWSC, 2018). LWSC has executed very robust project management processes and procedures that ensure value for money in the implementation of the projects. The company also ensures that financial and economic appraisal of all projects is conducted before committing any funds. Qualified examiners appointed by the shareholders also audit the projects. These persons report to the Audit Committee of the Board of Directors.

## 4.8. CONCLUSION AND WAY FORWARD; LESSONS LEARNED

Considerable investment is needed in water provision to meet Zambia's Vision 2030 and the Sustainable Development Goal on water and sanitation. There is therefore need to consider the opportunity for partnerships with non-government organizations and other players like pension funds, which may have resources they can put into the project. Public-private partnership projects can also be pursued to implement projects, considering the huge investment gap. However, a possible challenge in pursuing this track is that most private investors will shy away from committing their resources due to their concerns about returns on their investments. On account of Zambia's expected energy deficits, the sector must begin to consider alternative energy sources to run the water system, which is heavily reliant on hydroelectricity supplied by ZESCO. This has become very expensive.

The realities of climate change can no longer be ignored such that stakeholders in the water sector have included climate variability in their planning. The efforts being made by actors in the water sector to work together have increased the replication of activities. In some cases, this outcome expedited responses to problems as the various stakeholders use their resources to achieve common goals. The stakeholders have also realized the need to work closely with the central Government, which requires that a cordial relationship be maintained. This relationship is maintained mainly by keeping the Government informed about the contributions of stakeholders. In turn, this knowledge allows the the Government to call on stakeholders when certain activities are being rolled out.

A critical lesson learned during the implementation of improvement projects is that skills should be transferred to local personnel, as some of these projects happen once in a long time. Therefore capacity should be built within the country to undertake some major projects. LWSC has been able to do so within its project team. Now the team can undertake a complete project proposal, including preparation of the Bill of Quantities, the implementation of a project, and deal with sustainability matters. The team has also built the capacity to undertake project briefs and environmental impact assessments, which are requirements for new projects. Another lesson learned is that projects should be undertaken as a total package to avoid delays arising from omissions. In other words, all aspects of the project, from conceptualization to final implementation, should be well thought out and documented. In future, consideration should be made for the project funds to cover affected persons where compensation is required. This measure is preferable to using counterpart funding that may be difficult to access due to other competing needs on the resources from the national treasury. Project steering committees have been formed, with representations from key stakeholders. This development has helped eliminate most potential problems across sectors and interagency red tape. The formation of the project team was also critical in ensuring focus and dedication in implementation, as staff members were dedicated to the project and not distracted by attending to operational issues that could also be very demanding.

CHAPTER 5

# Water supply needs and solutions for Windhoek

A case study of Windhoek by
Dr Godfrey Tichaona Pazvakawambwa
and Plan Petrine Sem

Windhoek, Wingoc Direct Potable Reuse Plant (since 1968)

## 5.1 INTRODUCTION AND BACKGROUND

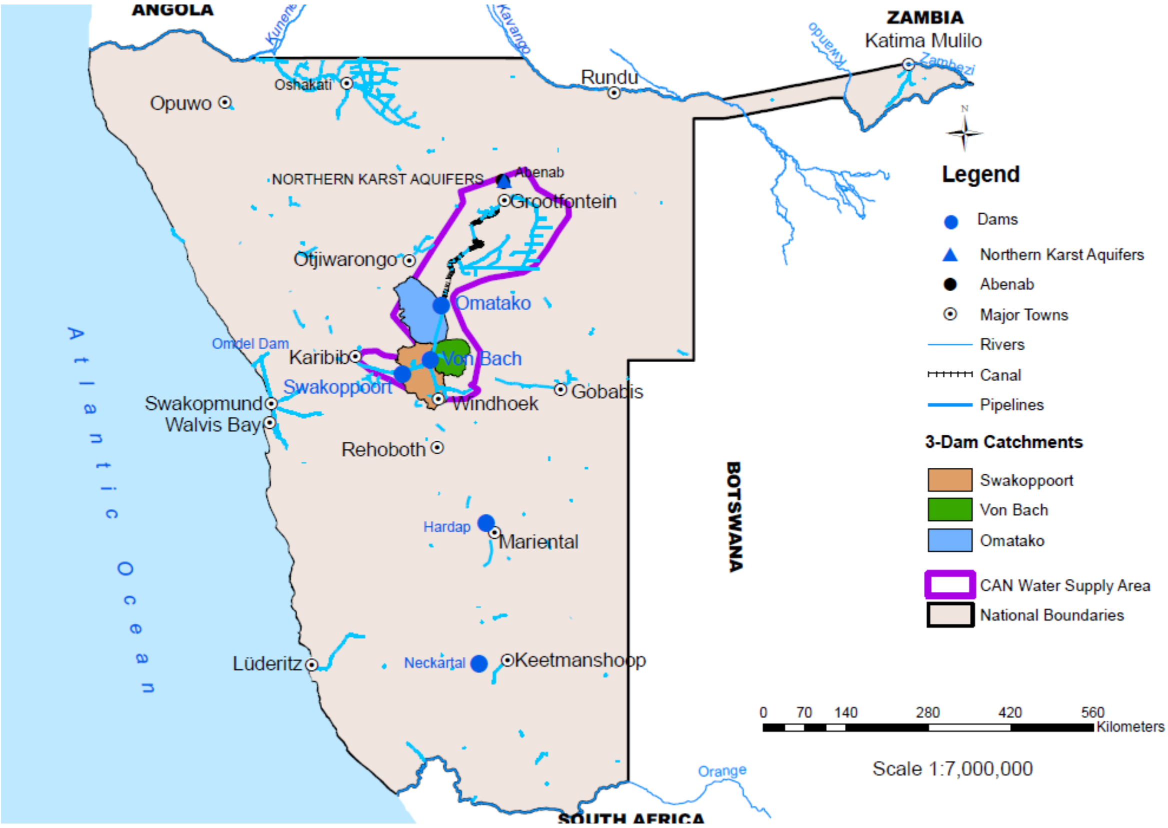
The worldwide forecast estimates that half of the global population could be facing water shortages by 2030, where demand is predicted to exceed supply by approximately 40 per cent (Connor, 2015). With climate change challenges, the situation of many water-stressed cities like Windhoek is likely to worsen, unless sustainable sources are developed and adaptive water supply solutions are deployed.

Namibia, situated in the south-western corner of Africa, is the most water-scarce, arid to semi-arid country in Africa south of the Sahara. Namibia, site of the Namib Desert, will remain continue to be more vulnerable to climate change unless vigorous adaptation and mitigation measures are taken. The country shares perennial rivers with bordering countries (Zambezi River - Zambia; Kwando/Linyanti/Chobe River - Angola and Botswana; Okavango River - Angola and Botswana; Kunene River - Angola; and Orange River - South Africa); see figure 5.1.

Windhoek, the country's capital, receives low average and highly variable rainfall (370 mm). The city gets its water from the Von Bach, Swakoppoort and Omatako Dam, respectively, 70, 90 and 160 km away (see figure 5.1). The city's water supply is highly variable and cannot match its growing water demands, especially during prolonged droughts. The need to develop reliable and sustainable sources in the face of climate change and mushrooming informal city settlements is compromised by limited access to funding and distant water sources.

For decades, Windhoek has faced water supply challenges due to frequent drought, and accelerated population growth due to rural-urban migration because of perceived favourable economic opportunities. In the

Figure 5.1: Location map of Windhoek, CAN water supply area, 3-dam catchments




short term, Windhoek may have succeeded in coping with the situation by stretching its limited potable water resources through multiple-source uses, employing adaptive drought response plans, and implementing strict water management strategies that are technology- and research-based (Lahnsteiner and Lempert, 2007; Van Rensburg and Tortajada, 2021). However, these adaptive strategies are being overtaken by climate change which is projected to cause even warmer and drier conditions than at present.

Nevertheless, Windhoek offers lessons in the sustainable utilization of available water resources in the short to medium term. In the long term, the future of water supply is highly uncertain unless lasting, sustainable sources are developed. This chapter examines how Windhoek has historically dealt with water scarcity and how this will be affected by climate change.

### 5.1.1. Location and background of Windhoek

Windhoek sits on the Khomas Plateau at an elevation of ±1,700 m above mean sea level and is at coordinates S 22°34'12", E 17°5'1", almost at the country's geographical centre in Khomas Region. The city is centred around hot springs (Otjomuise, meaning "place of steam" in a local language and Ai-Gams, meaning "fire water") in the rocky mountainous areas. Due to the mountainous topography of Windhoek, much of the city's municipal land comprises slopes greater than a gradient of 1:8. This terrain requires a robustly designed water supply infrastructure network to avoid excessive water pressures that can result in water losses.

Windhoek's nucleus developments started around 1840 with the arrival of German colonialists. About 80 years later, the South African administration took measures to further develop the city (Frayne, 2007; Mostert, 2017). Although the city has been growing steadily for over 180 years, recent years have been marked by a high acceleration of urbanization and informal settlements. A shortage of land saw the city extend its previous boundaries in 2012 to an estimated coverage of 5,133 km$^2$.

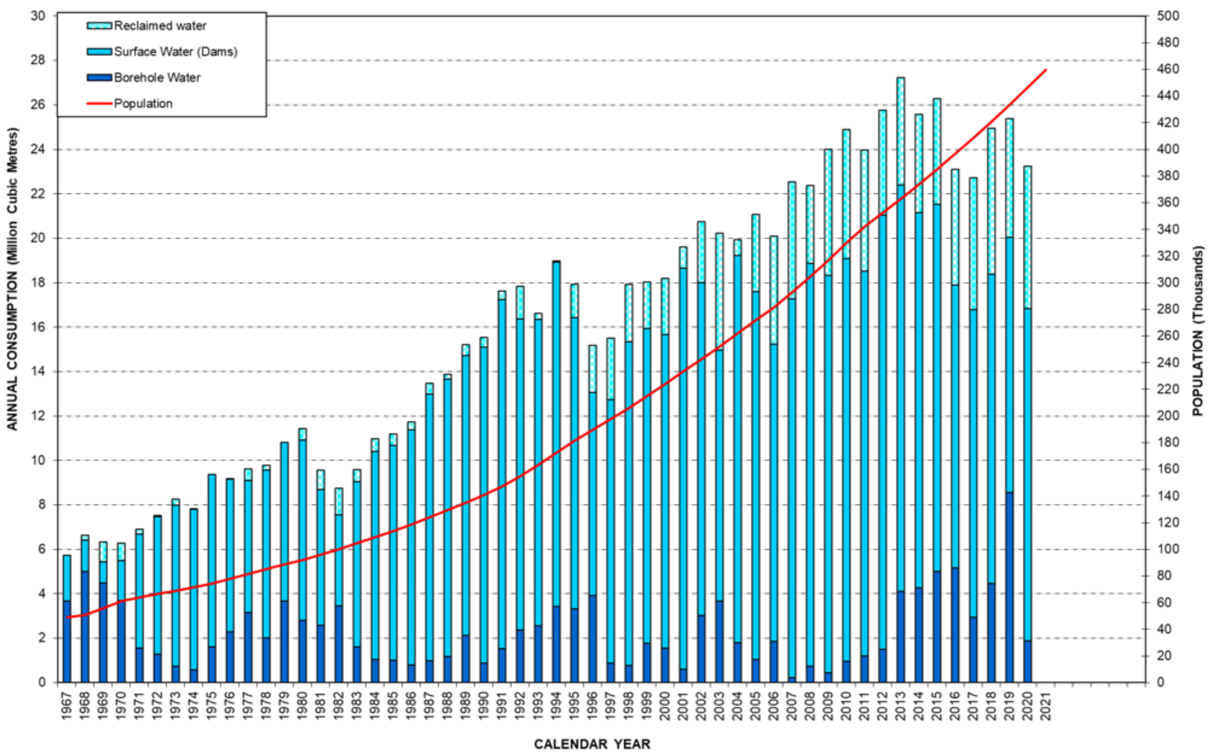
### 5.1.2. Population growth and historical water supply requirements of Windhoek

Windhoek remains a prime destination for Namibians looking for a better life in an urban setting,  the main draw being its position as the nation's administrive and economic cntre. Weber and Mendelsohn (2017),  say rural migrants seeking employment in Windhoek usually stay in the townships of Katutura, Goreangab, Wanaheda, Otjomuise and the north-western suburbs. Nghinomenwa (2020), Weber and  Mendelsohn (2017) maintain that some of the migrants typically end up staying in the informal settlements, which had a population of ±100,000 (41,900 households) out of a total population of some  430,000 in 2020. These informal settlers earn less than USD 1 per day. In contrast, Windhoek's central and southern parts, including the central business district, host middle- to high-income earners, mansions and malls (Uhlendahl et al., 2010). Since the nation's independence in 1990, the informal settlements that started as temporary "reception areas" accommodating poor migrants have mushroomed in the last 30 to 40 years. Frayre (2007), Karuaihe and Wandschneider (2018) further indicate that after independence, the demolition of the former combined compounds, which used to accommodate cheap labour contract workers, and the upgrading of "single quarters" gave rise to the city's informal settlements.

In 1991 Windhoek had 141,300 people, and only 3 per cent of those persons resided in informal settlements. By 2002, Katutura, a low-income household suburb of Windhoek, had been overgrown by informal settlements; at a rate of 9.5 per cent per year (World Bank, 2002).  The 2011 census shows that of the 36  per cent increase in Windhoek's population between 2001 and 2011, 71 per cent lived around Katutura (NSA, 2011; Pazvakawambwa, 2018). By 2004, the population had reached 250,000. Of this, 29 per cent were informal settlers. By 2011, informal housing in Windhoek was estimated to be 32 per cent. In 2016, the population in the city was ±370,000 and was expected to double within the next 20 years, which would put pressure on water service provision (Van Rensburg, 2016). Windhoek's population grew from an ±325,858 in 2011 to a projected ±430,000 in 2020 (NSA, 2011), the annual population growth rate ranged between 3 per cent and 3.48 per cent  from the period 2017 to 2021 (City of Windhoek, 2021). The proxy water demand (water supplied from 1967 to 2020) due to the city's increase in population is shown in figure 5.2. The greatest volume of water (27 $Mm^3/a$) was supplied in 2013, which dropped to of ± 23 $Mm^3$/ in 2020.

Since 2000, informal settlements, home to poor households without land tenure, have outstripped the city's ability to provide services. Two categories of these

Figure 5.2: Growth of Windhoek population, related water supply 1967–2020



informal settlements receive only partial city water supply services. These are households that were resettled non-voluntarily from another area and non-lease informal settler land occupants where the city provides minimum basic services (water and latrines) at communal points.

The city introduced post- and pre-payment water services. Each has its advantages and disadvantages. The post-payment system uses a community tap, where a small group of households, usually four or five, use one tap. The monthly cost is shared among them and paid to a committee member, who then pays the municipality. The pre-payment system, which consists of water points, requires each household to use a pre-payment card to access water. However, city services have failed to keep pace with the high annual influx of people. As a result, water supplies to informal settlements have declined progressively, contributing to the difficulties in providing drinking water citywide (Lewis et al., 2019).

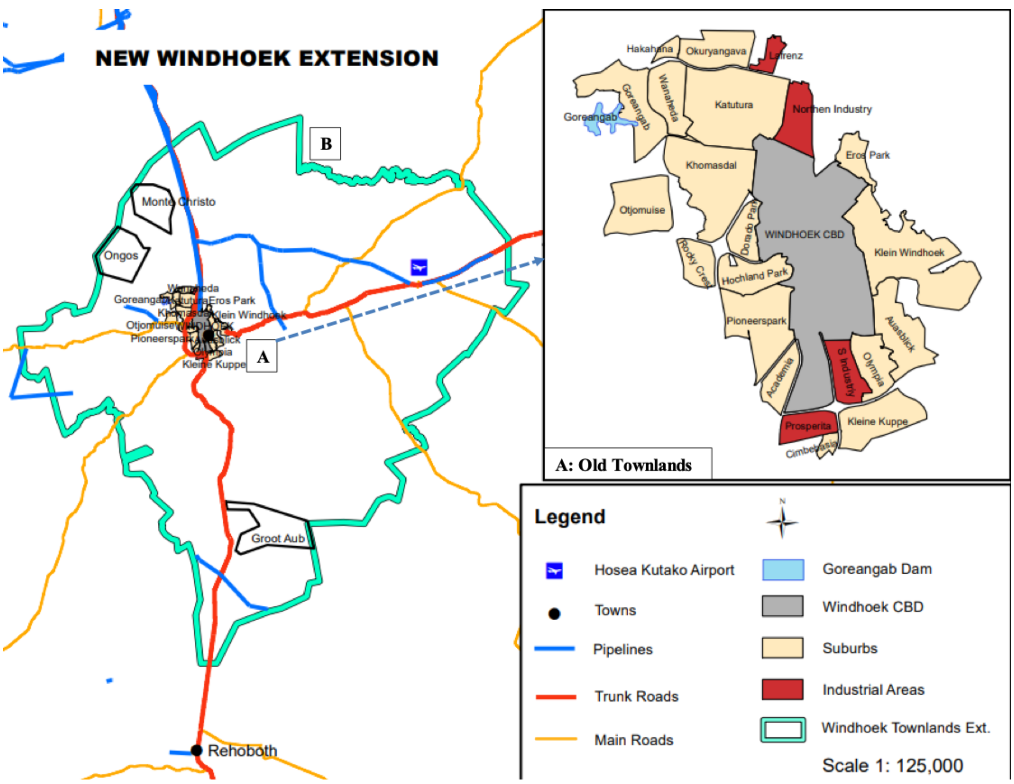
The challenges of water provision mirror the urban planning challenges in Windhoek, which is the lack of funding, specifically for housing that can accommodate the poorer population. Other weaknesses are poor technical planning capacity and outdated regulations, which neither account for new urban realities nor sensitive environmental conditions (Remmert, 2017). In the past, the urban developments in Windhoek were aimed at the higher-income groups, neglecting the development of more affordable housing for the poor. However, the planned massive formal low-cost housing developments (28,000 to 30,000 housing units to be developed in the next 30 years) by private investors in Ongos, Monte Christo farms and Goreangab western areas of the city will likely provide significant affordable houses and services like potable water. However, it remains uncertain whether the intended beneficiaries will be the final occupants of the houses.

### 5.1.3. Extended boundaries and expansion of the city

Windhoek's municipal boundaries of have been extended to include former peri-urban areas. It should be noted that the demand for land was made worse because the southern part of the city sits atop Windhoek's aquifer, an area designated for groundwater protection.

Windhoek comprises a city centre, industries, high, medium and low-income suburbs, and informal settlements. Major industrial areas include  Prosperita, Southern and Northern Industrial zones, Lafrenz, and Brakwater. Recently, Windhoek has undergone a high

Figure 5.3: Old townlands (A), extended boundaries of Windhoek (B)



degree of urbanization and equally rapid growth in informal settlements. This condition has resulted in a shortage of land, and in 2012 prompted the city to extend its previous boundaries to an estimated coverage area of 5,133 km$^2$ (see figure 5.3).

The boundaries and peri-urban areas were expanded to accommodate surrounding farms. The farms have been subdivided into mainly residential areas. On 30 September 2011, the minister of regional and local government, housing and rural development gazetted the Alteration of the Boundaries of the Local Authority Area of Windhoek (Government Gazette No. 4801 of 2011) to extend Windhoek's  boundary to a radius of more or less 30 kilometres in all directions. Areas that used to lie outside the city now fall within the municipality. Some of these areas are Groot Aub in the south, Seeis to the east, and Baumgartsbrunn to the west. Roughly 325 properties - mainly farms, farm portions and townships - have been added to Windhoek. However, the required water service coverage and infrastructure are still lagging due to the additional financial obligations and capital requirements. While the city has legislative powers within its local authority jurisdictional area to provide services, the limited or absence of resources for expansion is challenging. According to Windhoek's Strategic Directions Workshop held in early 2021 on the city's Spatial Development Framework (2021 to 2040), there is little to no land in municipal ownership suitable for servicing low and ultra-low-cost income groups. The settlement demands in the non-urban periphery pose complications for the regulatory system. The available and accessible public open land is equally threatened by private developers eager to exploit the immediate commercial opportunities, but with no consideration for the needs of the existing and future low-income population. Despite these setbacks, the city is committed to the mandatory expansion of the services network before legal developments arise and new settlements sprout.

### 5.1.4. Water governance

#### 5.1.4.1 Institutional framework

Who is in charge of the water supply in Windhoek, and how is water governed? Various institutions are responsible for water supply. The Department for Water Resources Management in the Ministry of Agriculture, Water and Land Reform (MAWLR) is responsible for overall water resources management in Namibia. The same department is responsible for the overall wastewater discharge, groundwater permit issuances, and compliance with users, including Windhoek and NamWater.The same department is responsible for the overall wastewater discharge, groundwater permit issuances, and compliance with users, including Windhoek and NamWater. The department oversees and is the secretariat for 14 functional river basin committees, including the Upper Swakop River Basin Management Committee, under which Windhoek falls. The committee continues to lobby and advocate against the catchment pollution caused by Windhoek, which is upstream in the basin that drains into the Swakoppoort Dam reservoir and is hypereutrophic due to pollution. Water pollution emanates from Windhoek's wastewater treatment plants and some wet industries (NamWater, 2021).

**Table 5.1: Water supply agencies' contribution to CAN supply area, water governance institutions types**

<table>
<tr><th>Water Source Description</th><th>Approximate Yield (Mm$^3$/a)</th><th>Total % Contribution</th><th>Supplying Agent</th><th>Type of Water Governance Institution</th></tr>
<tr><td>Surface Water</td><td rowspan="2">20</td><td rowspan="2">56</td><td rowspan="4">NamWater</td><td rowspan="4">Limited Company; 100% State Owned</td></tr>
<tr><td>Omatako, Von Bach; Swakoppoort Dams (95% assured yield)</td></tr>
<tr><td>Groundwater</td><td rowspan="2">6.7</td><td rowspan="2">18</td></tr>
<tr><td>Berg Aukes Mine & Boreholes; Kombat Mine; Goblenz Boreholes; Seeis Boreholes;</td></tr>
<tr><td>CoW Aquifer/Boreholes;</td><td>1.7</td><td>5</td><td>CoW</td><td>Public Authority</td></tr>
<tr><td>Recycled Water</td><td rowspan="2">7.5</td><td rowspan="2">21</td><td rowspan="2">Wingoc under Public Private Partnership</td><td rowspan="2">Public Private</td></tr>
<tr><td>Old Goreangab Recycling Plant; New Goreangab Reclamation Plant</td></tr>
<tr><td></td><td>35.9</td><td>100</td><td></td><td></td></tr>
</table>

Source: Pazvakawambwa, 2018

NamWater is a State-owned bulk water supplier that operates dams, pipelines and water treatment plants countrywide. The utility provides some 74 per cent of the bulk potable water to Windhoek and other centres. NamWater draws its water from the three integrated dams and from the northern boreholes. Then it supplies Windhoek, which sells the water to households and businesses.

Several agencies supply Windhoek with potable water (see table 5.1). The Windhoek Municipality  draws its groundwater from artificially rechargeable aquifer boreholes, which it owns and operates Windhoek Goreangab Operating Company (WINGOC), jointly owned by Windhoek Municipality and a Germany company, is contracted to operate the New Goreangab Water Reclamation Plant (NGWRP). The plant supplies approximately 21 per cent of the bulk drinking water to Windhoek. The remainder comes from Windhoek's boreholes.

### 5.1.4.2 Water tariff approvals

Legally, the water tariff approval is the responsibility of the water regulator as provided by the Water Resources Management Act (2013). However, the regulator is still being established. Therefore, the *de facto* arrangement is that NamWater and the various local authorities, including Windhoek, prepare their water tariffs, which are submitted to Cabinet through their relevant line ministries for approval. MAWLR (in the case of NamWater) and the Ministry of Urban and Rural Development (in the case of the local authorities) present the respective tariffs to Cabinet before being approved and published in the Government Gazette.

**Table 5.2: Legal framework, policies, plans guiding water and environmental sectors**

| Number | National, Multisectoral, Environment, Water Acts, Policies and Plans | Year |
|---|---|---|
| 1 | Water Act No.54 being superseded by | 1956 |
| 2 | Articles 95 and 100 of the Constitution | 1990 |
| 3 | Water Supply and Sanitation Sector Policy | 1993 |
| 4 | Environmental Assessment Policy | 1993 |
| 5 | National Development Plans (NDP) 1 to 5; 5-year plans started 1995 & NDP 5 (2017–2022) | 1995 |
| 6 | Namibia Water Corporation Act No.12 | 1997 |
| 7 | National Water Policy | 2000 |
| 8 | Vision 2030 | 2004 |
| 9 | Environmental Management Act No.7 | 2007 |
| 10 | Water Supply and Sanitation Policy | 2008 |
| 11 | Revised Green Scheme Policy | 2008 |
| 12 | Integrated Water Resource Management Plan for Namibia | 2010 |
| 13 | **Water Resource Management Act No.11 | 2013 |
| 14 | Harambee Prosperity Plan I (2016–2020) and II (2021–2025) | 2016 |
| 15 | Urban and Regional Planning Act No.5 – (guiding Windhoek municipality) | 2018 |
| 16 | National Water Tariff Water Policy (source: MAWLR, 2021) | Pending |

** Water Management Act (2013)

### 5.1.4.3 Government support to sustainable water supply security

Widespread drought across Namibia propelled the Government committed to tackle Windhoek's acute water shortages. The President appointed the Cabinet Water Supply Security Committee, assisted by a Technical Committee of Experts comprising former and current Government technocrats and national experts on water resources development and management. The overriding function of the Cabinet Committee is to review all proposed water supply solutions by various stakeholders, including proposals by the MAWLR, NamWater and Windhoek municipality.  The Cabinet Committee's other functions include presenting to Cabinet fortnightly, for decision-making, the detailed and costed implementation plans to avert short- and long-term water supply crisis in Windhoek. The Cabinet Committee also sets the priorities, monitors the implementation plan and submits reports on a fortnightly basis to the Cabinet on progress made. In 2016, when Windhoek's water crisis solutions were drawn and were under implementation, the Cabinet Committee immediately turned its attention to other national water supply critical areas in a phased approach, which has been ongoing.

### 5.1.4.4 Legal framework, regulations on water resource management and supply

Various water resource management legislations, policies and plans have been approved in post-independence Namibia. Articles 95 and 100 of the Constitution of the Republic of Namibia are the pillars for the use, management and protection of the sovereign water resources. These Articles indicate that the Government must adopt policies for the maintenance of ecosystems essential for the country's ecological processes and biological diversity, as well as the utilization of living natural resources on a sustainable basis for the benefit of all Namibians, present and future. Guided by the multisectoral five-year national development plans, Vision 2030 and Harambe Prosperity Plans, the rest of the Water and Environmental Acts, Policies and Plans are listed in table 5.2.

## 5.1.5. Legal framework, policies and strategies on climate change

The Namibian regulatory framework and strategies for climate change are summarized in table 5.3. In 1995, Namibia ratified the United Nations Framework Convention on Climate Change. It became legally obligated to adopt and implement policies and measures designed to mitigate the effects of climate change and to adapt to such changes. The ultimate objective of the convention is to stabilize greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system.

Namibia established the National Climate Change Committee in 2001 with the main function of advising and making recommendations to Government on climate change, including how to meet its reporting obligation to the Convention. Reporting to the Convention was followed by the compilation of the Climate Change Vulnerability and Adaptation Assessment of Namibia in 2008, and this was spearheaded by the Ministry of Environment and Tourism. The primary focus of the vulnerability assessment included the agricultural sector, rural development and the water sector. In 2010, the National Policy on Climate Change for Namibia was also compiled.

**Table 5.3: Climate change framework for Namibia**

| Number | Climate Change-related Acts, Policies, Plans, Adoptions & Documents | Year |
|---|---|---|
| 1 | National Climate Change Committee | 2001 |
| 2 | Climate Change Vulnerability and Adaptation Assessment of Namibia | 2008 |
| 3 | National Policy on Climate Change for Namibia | 2010 |
| 4 | Disaster Risk Management Act No. 10 | 2012 |
| 5 | National Climate Change Strategy and Action Plan (2013–2020) | 2013 |
| 6 | Paris Climate Agreement - Adopted by Namibia | 2016 |

The National Climate Change Policy takes a cross-sectoral approach and elaborates on climate change adaptation and mitigation in Namibia. The policy outlines a coherent, transparent and inclusive framework on climate risk management in accordance with Namibia's National Development Agenda legal framework and environmental constraints. The Policy was followed with the compilation of the National Climate Change Strategy and Action Plan, encapsulating the guiding principles responsive to climate change that are effective, efficient and practical. It further identifies priority action areas for adaptation and mitigation strategy and action plan. The Action Plan introduced various funding mechanisms as well as Government funding; for example, Adaptation Fund, common Green Climate Fund and other existing funding mechanisms, such as those of the Global Environmental Facility as well as support through various institutions for the strategy, to come to fruition. These action plans have been extended to 2030 according to the Millennium Development Goals (MDGs).

Namibia's participation on the global agenda has been consistent and remarkable with the ratification of the Paris Climate Agreement in 2016. This robust framework provided for member countries like Namibia to boost efforts to combat global warming. The MDGs primary aim of ending worldwide poverty had its second phase, the 2015–2030 Sustainable Development Goals more geared towards climate change adaptation and mitigation (especially SDG 13). In 2016, the UN-Habitat III Conference held in Quito, Ecuador, came up with the New Urban Agenda, to provide momentum towards implementing Goal 11 that focuses on the development of cities incorporating greener and eco-friendly technologies while being more inclusive, safe, resilient and sustainable.

Namibia also promulgated the Disaster Risk Management Act in 2012. The Act allows the establishment of agencies for disaster risk management that cover, among others, drought and flood events from climate change. This Act provides for an integrated and coordinated disaster management approach that focuses on preventing or reducing the risks of disasters, mitigating the severity of disasters, emergency preparedness, rapid and effective response to disasters and post-disaster recovery.

To ensure sustainable long-term access to water, sound management and conservation of the country's water resources with the uncertainty of climate change, Namibia, through its Nationally Determined Contributions and during the Conference of the Parties, COP26 (2021), has restated the adoption of the following adaptation options:

- Promote efficient water use, particularly in water harvesting techniques, irrigation, conjunctive use of groundwater and surface water as well as artificial recharge of groundwater

- Promote and prioritize the use of desalination techniques

- Improve water demand management and encourage Integrated Water Resources Management

- Establish nationwide monitoring and control of groundwater as well as wastewater discharges

### 5.1.6. Windhoek's Draft Integrated Climate Change Strategy and Action Plan

Given the foregoing frameworks, Namibia's sector ministries, departments and municipalities are being guided to undertake their own climate change assessments and draft their respective plans. Thus, Windhoek participated in co-producing knowledge for an urban climate resilience project that brings together city decision makers, community representatives, and climate and social science researchers to achieve the following objectives:

- Help decision makers better understand climate science

- Help climate scientists better understand the needs of decision makers

- Help city authorities design effective development policies underpinned by climate science

This co-production process was a significant input to the Future Resilience for African Cities and Lands (FRACTAL) project, part of the multi-consortia Future Climate for Africa programme (SEI, 2019). The project started in 2018 with the Stockholm Environmental Institute (SEI, 2019) partnering with Windhoek in developing the city's first integrated climate change strategy and action plan, which aimed to be a model for other African cities. Adapting the policy and finance models under the United Nations Framework Convention on Climate Change, vulnerability assessments, capacity-building and community-based adaptation, the city compiled the *Climate Change model Assessment for Windhoek.* Through the FRACTAL project, the draft

Windhoek Integrated Climate Change Strategy and Action Plan 2020–2027 has been compiled (Windhoek city, 2020) and is awaiting the approval of the Municipal Council of Windhoek.

The draft action plan presents the Windhoek Climate Change Vulnerability and Response approach (Climate Change Adaptation and Mitigation) and illuminates the focus areas of climate change. These focus areas include:

1. Water security and efficiency, that is water demand management measures.

2. Sustainable energy and low carbon development.

3. Public awareness and capacity-building.

4. Biodiversity and ecosystem goods and services.

5. On the built environment: (i) waste minimization and management; (ii) human settlements (32 per cent of settlements in Windhoek were informal in the 2011 national census); (iii) healthy communities; (iv) sustainable transport=; (v) disaster preparedness; (vi) sustainable urban agriculture.

Via these focus areas, Windhoek continues to embrace socioeconomic and cultural co-benefiting ecosystem-based adaptation, that is, conservation of biodiversity, the integration of the sustainable use of biodiversity and ecosystem services into an overall adaptation strategy in a cost-effective approach.

The above-outlined work plan in Windhoek, and similar work in eight other African cities through the wider project, focuses on the need to adapt to climate change (Goal 13: climate action), and the need to make cities safe, resilient and sustainable (Goal 11: sustainable cities and communities). The work spans other related goals, including ensuring the availability and sustainability of clean water and adequate sanitation (Goal 6) and enhancing the health and well-being of people (Goal 3).

The current strategies to sustainable water supply that Windhoek is pursuing dovetails into the above policies and action plan framework.

### 5.1.7.Climate changes likely to affect Namibia

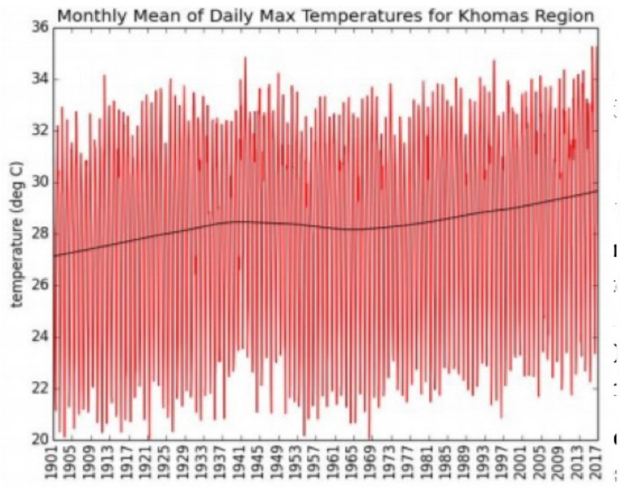
Historically, Namibia's climate has been largely influenced by the recurring El Niño-Southern Oscillation and the Benguela Current that draws icy-cold waters from the Southern Ocean and carries them northward along the west coast of Africa. These cold waters prevent rain clouds from developing over the southwest coast of Africa, contributing to the dry climate in Namibia of the Kalahari and Namib deserts. These areas are semi-arid, hot areas with a dry climate and erratic rainfall. The annual rainfall ranges from less than 50 mm along the coast to 350 mm in the central interior and 700 mm in the north-east Zambezi Region. Of the rainfall received, 83 per cent is lost to evaporation, 14 per cent in transpiration, 2 per cent becomes run-off in the rivers, while 1 per cent seeps underground, which may later be extracted through boreholes for utilization. The Namibia Meteorological Services reported in 2021 that the annual evaporation ranges from 2,600 mm in the north east to 3,700 mm in the central-southern area. Evaporation is highest October to December. Dams in Namibia can lose between 20 per cent and 85 per cent of their water through evaporation within one season (NMS, 2021).

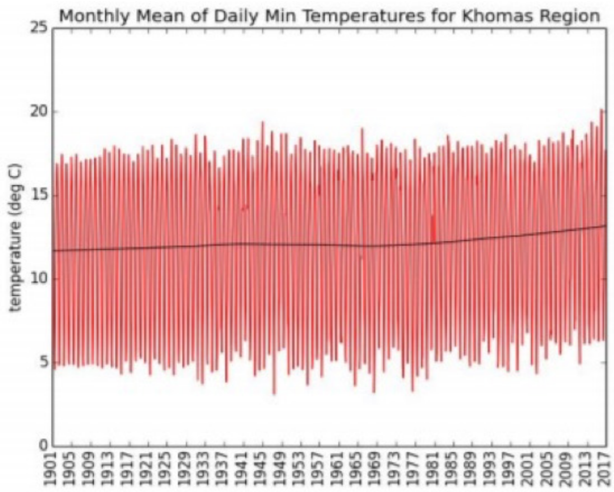
Changes to climate and their effect on Namibia's water sources are predictably eminent. These sources include perennial transboundary rivers, dams on ephemeral rivers, groundwater, fountains, desalinated seawater and recycled water.

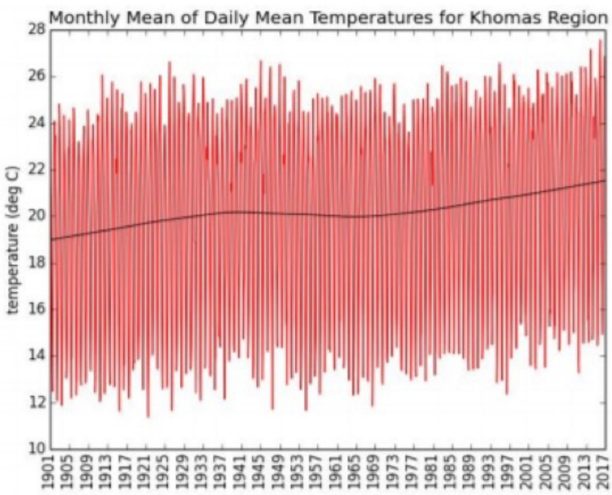
Temperatures over Southern Africa have increased rapidly over the last five decades at about twice the global rate of temperature increase (Archer et al. 2018). Further drastic increases, in the order of 6°C by the end of the century relative to the present-day climate, may occur over the central and western interior regions under low-mitigation futures. Windhoek's microclimate is semi-arid. Annual average temperatures rise above 18ºC. July is the coldest month with the average at 13.1ºC. December is the hottest month when the temperature average 23.5ºC. As depicted in figure 5.4, the Khomas Region (covering Windhoek areas) shows an increasing trend in temperature (1901 to 2017).

According to Winsemius et al. (2018) and the World Bank Group (2021) spatial drought variability projection of Southern Africa, the change in the likelihood of severe drought each year in Namibia will increase as 2050 approaches (see figure 5.5). Detecting rainfall trends is even more difficult, especially concerning highly variable arid climates such as Namibia's. Considerable spatial heterogeneity in the trends has been observed, but it

Figure 5.4: Khomas historical temperatures



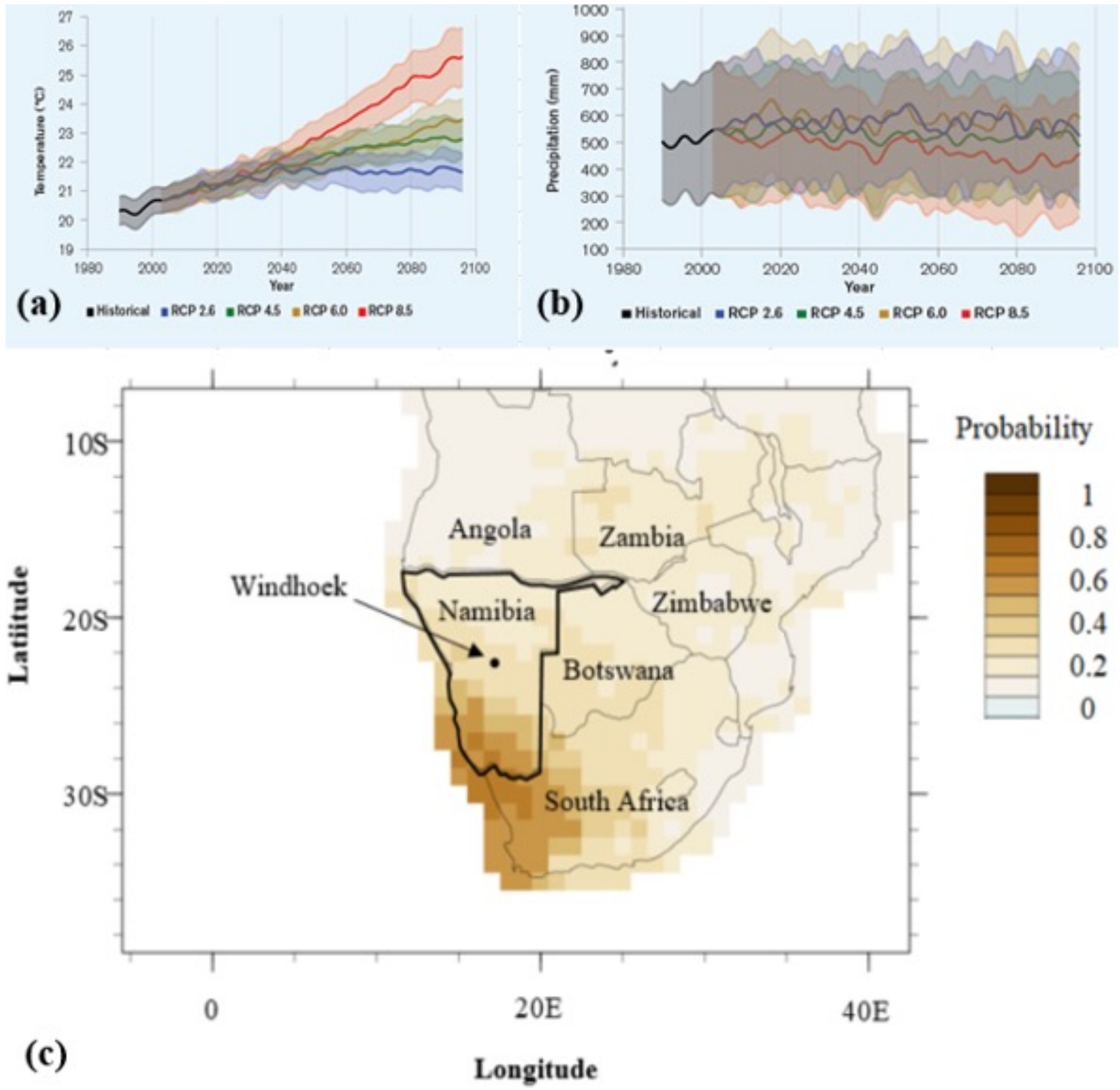

now appears that Namibia's northern and central regions of Namibia are experiencing a later onset and earlier cessation of rains, resulting in shorter seasons in most vicinities. Equally, according to Maúre et al. (2018) the projections from an ensemble of 25 regional simulations out of the CORDEX suite of models analysed for Southern Africa scenarios under global warming levels of 1.5ºC and 2.0 ºC are predicted to be drier (see figure 5.5). This is despite the uncertainties about the projected changes of temperature and precipitation.

There has been a statistically significant decrease in the number of consecutive wet days in various locations, and increases in measures of rainfall intensity can be observed (DRFN, 2008). The degree to which rainfall in Namibia will be reduced is not obvious, but they are likely to be more intense. Stronger variability is likely to remain the key aspect of Namibia's climate in the future (DRFN, 2008). These climate change effects are difficult to monitor nationally, but they may already prevail in Namibia. Similarly, this phenomenon may even be present at the micro level in Windhoek, where droughts and rainfall variability is high.

### 5.1.8. Windhoek historical variable rainfall and drought periods prompting adaptive interventions

The incessant droughts that historically prevailed around Windhoek and its surface potable water supply sources prompted adaptive interventions and solutions (see figure 5.6).

Figure 5.5: Projected average temperature (a); annual average precipitation for Namibia - period 1996–2005 (b); ( c) projected changes in annual likelihood of severity of drought




Source: Adopted from the World Bank Group, 2021

Some of the adaptive and reactive water supply source interventions following drought periods include:

1. The 1960–1964 drought period gave rise to the establishment of the first direct potable reclamation (DPR) plant in 1968 (Van der Walt, 2003; Van Rensburg, 2016), referred to as the Old Goreangab Water Reclamation Plant (OGWRP).

2. The long drought periods between 1991 and1997 prompted the improvement and upgrades of OGWRP- based on contemporary and available water treatment technologies. The drought also gave birth to the New Goreangab Water Reclamation Plant (NGWRP) with a production of 21,000 m3/d in 2002 (Du Pisani, 2004).

3. The 2015–2019 dry period was one of the factors that pushed Windhoek city officials to consider establishing the second DPR, which is being planned under the ongoing feasibility study (Windhoek city, 2021).

### 5.1.9 Historical rainfall patterns and trends for Windhoek

According to Pazvakawambwa and Ogunmokun (2017), despite rising temperatures being an eminent sign of global warming, the historical rainfall trend for Namibia, in particular Windhoek, is less depictive of the global warming trends save for the high rainfall variability and the incessant droughts that prevail through the period of analysis from 1892 to 2012. The seasonal and irregular fluctuations of the mean monthly rainfall levels do not suggest an upward or downward trend over the century. The time series plot of Windhoek monthly rainfall from 1891 to 2012 suggests the series is stationary, since the mean and variance of the series did not seem to change with the level of the series. Even though the results indicated constant mean monthly rainfall, the limitation was that the analysis was based on a small spatial area to rule out climate change effects. The time series decomposition plots of the monthly rainfall is presented in figure 5.7.

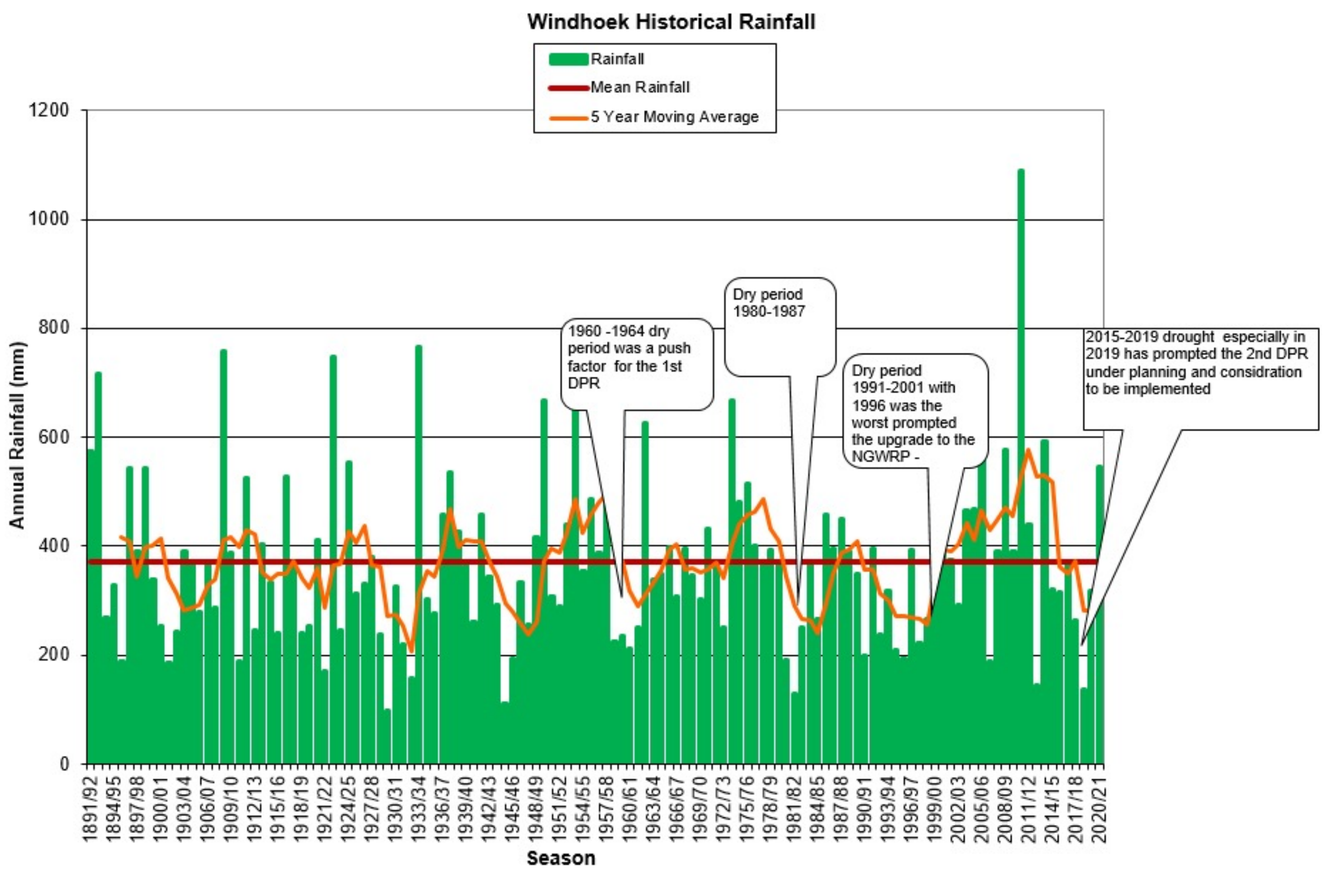
Monthly rainfall was highly varied with a minimum of 0 mm and a maximum of 321 mm. The average monthly rainfall was 31.2 mm (95 per cent confidence interval: 28.2 mm, 33.7 mm) with a standard deviation of 48.8 mm. There were notably high rainfall figures in February 1923 (303.0 mm), January 1893 (308.0 mm), March 1954 (312.2 mm), January 2011 (320.9 mm) and January 2006 (321.3 mm).

## 5.2. HISTORICAL, PRESENT WATER SUPPLY SOURCES AND DEVELOPMENT INTERVENTIONS

### 5.2.1. General

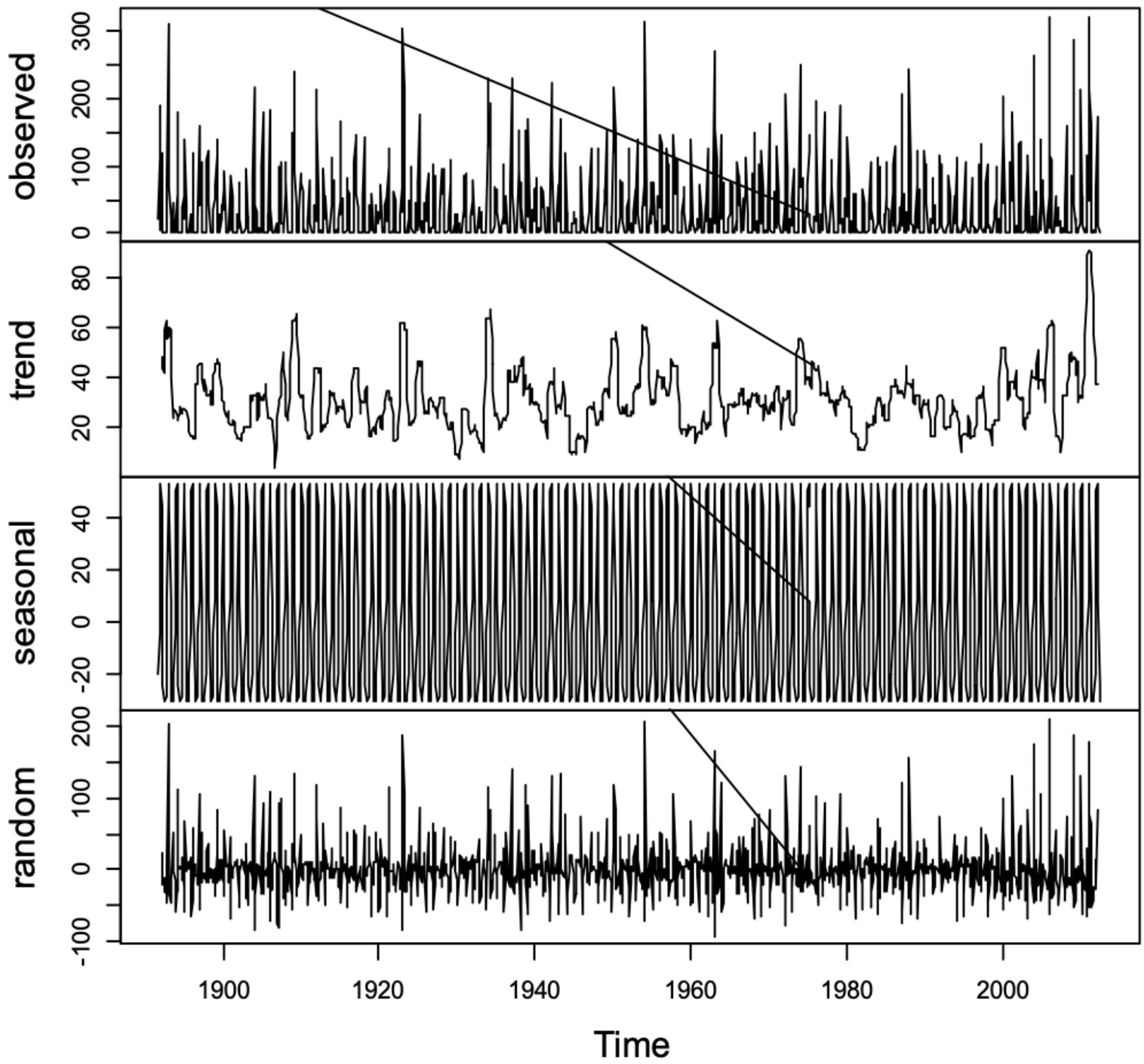
When the Windhoek nucleus settlement started in 1884, 12 springs provided domestic and irrigation water for consumption crops. In 1933, when boreholes and springs were stressed, the Avis Dam on the ephemeral Klein Windhoek River was commissioned. This was followed by the construction of the 17m high, 3.6 $Mm^3$ capacity Goreangab Dam on the ephemeral Arebbusch River, which was commissioned in 1958. The timelines of sources developed to supply Windhoek are depicted in figure 5.8.

Figure 5.6: Windhoek historical variable rainfall (1892–2021) and drought periods prompting adaptive interventions




Source: NamWater, 2021

Figure 5.7: Decomposition of Windhoek's rainfall time series



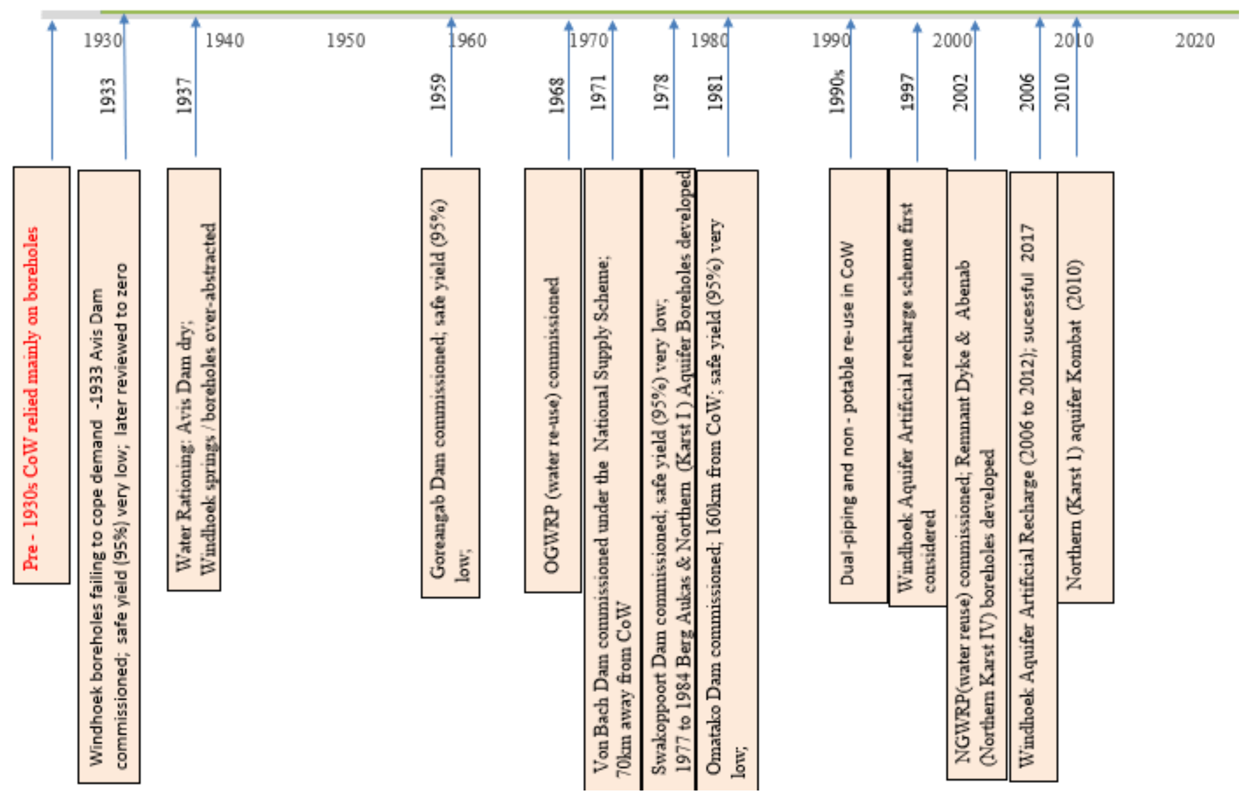

When these two small dam water sources (the Avis and the Goreangab) in Windhoek could not meet the city's growing water demand, the existing present sources, the integrated 3-dam system, were then developed under the National Supply Scheme. The characteristics of five dams constructed to supply Windhoek are given in table 5.4 and water supply network schematic in figure 5.9.

The upstream Avis Dam that was established first in Windhoek has since been decommissioned as a water supply source. It now serves as a recreational reservoir as well as recharging boreholes within its dam basin. The Goreangab Dam, the second established water supply dam in Windhoek, is downstream of the city drainage and is heavily polluted. Due to its increased pollution, the dam has been abandoned as a source for drinking water save for partially being utilized for irrigation of lawns after it is semi-purified at OGWRP (Pazvakawambwa, 2018). Despite the limited amount of water available, Windhoek has always managed to expand and grow in population, thus setting a good example for other cities facing similar problems.

The integrated 3-dam reservoirs, comprising the Von Bach, Swakoppoort and Omatako, herein referred as the 3-dam system, supply potable water to the Central Area of Namibia (CAN) water supply area, which includes Windhoek. The Von Bach Dam has a full supply capacity of 48 Mm³, Swakoppoort 63 Mm³ and the Omatako 45 Mm³. To counter high evaporation losses, water from the Omatako and Swakoppoort Dams are transferred into the deeper and smaller surface area Von Bach reservoir. The characteristics of the three-integrated dam system are given in table 5.4. The dams have different capacity to surface area and storage ratio relationships as illustrated in table 5.4 (Pazvakawambwa, 2018). The dams were designed to hold three-year mean annual run-off, giving a long residence time. The dams seldom spill. The Omatako is prone to more evaporation, due to its lower volume to surface area ratio. However, it has a higher storage ratio and on average fills up approximately once in 1.4 rainy seasons. On the other hand, the Swakoppoort requires 3.5 average rainy seasons to fill. The combined 95 per cent safe yield of the three dams is ±13 Mm³/a, which increases to 20 Mm³/a when the three dams are operated optimally as an integrated system to minimize evaporation. However, according to Bruce and Burger (2019), the combined safe yield of the integrated dams is questionable and, as such, a proposed figure of 10 Mm³/a has been advanced.

Water in the Von Bach reservoir is conventionally treated (screening, dosing, mixing, settlement clarifying, filtration and chlorine disinfection, storage and distribution) at the Von Bach Water Treatment Plant (VBWTP) to potable state and pumped to en route users in Okahandja and Windhoek cities. This integrated approach is supported by weekly monitoring of available water from all three dams and other sources through the use of the Central Area models. The monitored decision-making feedback information is shared among key stakeholders and water users (including domestic and all wet industries) in the planning and management of available resources. This integrated management approach of water sources and stakeholder involvement has contributed to the success of these short-term adaptive solutions. Windhoek's bulk water is supplied mainly by NamWater, the national bulk water agency. The city's groundwater comes from the Karst aquifers and disused mine pits. The water is conveyed via the Grootfontein – Eastern National Water Carrier Canal (ENWC) and blended with water abstracted from the 3-dam system. The raw water is treated at Von Bach and distributed to Windhoek (accounts for ±75 per cent of the water demand of CAN) and to the rest of the water demand centres of CAN.

Figure 5.8: Timeline of development of potable water sources for Windhoek



The 3-dam system is operated by NamWater, which supplies water to the whole CAN (see figures 5.1 and 5.9). The main inter-basin transfer to CAN is via the ENWC, where water from the Omatako Dam and other groundwater sources from the northern Karst areas near Grootfontein (approximately ±300 km to the north of Windhoek) is conveyed via a combined canal and pipeline system to Von Bach Dam. For decades now, the strategic extension of this water supply system under consideration has been to abstract water from the transboundary Okavango River via a still to be constructed pipeline that will link to the ENWC conveyance system. Groundwater from Kombat, Berg Aukas and Karst is transferred from the north and discharged at the Von Bach reservoir where it is treated and distributed to Windhoek, Okahandja and other customers. The Windhoek Municipality is responsible for the abstraction of groundwater from the Windhoek aquifer and water reuse treatment from NGWRP through public-private partnership arrangements.

Raw water is supplied direct from the Swakoppoort Dam reservoir to Navachab Mine, Karibib and Otjimbingwe downstream as part of CAN. Also, upstream of Von Bach Dam, Okakarara town and other smaller consumers are supplied from the water supply network that includes the ENWC (see figure 5.9).

The Von Bach Dam constitutes the central node in the CAN water supply system. The emergency groundwater from the Northern Karst aquifers—with maximum emergency yield of ±10 $Mm^3/a$ (still being confirmed through groundwater modelling) during drought periods—is abstracted from Kombat Mine (current abstracted volume 5 $Mm^3/a$; maximum potential 7.5 $Mm^3/a$), Berg Aukas Mine (current abstracted volume 4.4 $Mm^3/a$; maximum potential 7.5 $Mm^3/a$), and Karst 1 (maximum potential 1.48 $Mm^3/a$) and Karst 4 boreholes. The schemes are near Grootfontein town (about 400 km north of Windhoek) and conveyed via the Eastern National Water Carrier Canal system to Von Bach Dam, where this raw groundwater is mixed with the surface raw water from the 3-dam system. The water is then purified at the Von Bach Water Treatment Plant (VBWTP) and distributed to Windhoek and other water demand centres in CAN.

The historical developments of water supply sources for potable use in Windhoek have been described by Van der Walt (2003), Du Pisani (2006), Van Rensburg (2016), Lahnsteiner et al. (2018) as well as Tortajada and Van Rensburg (2020). Only highlights are presented here.

The Windhoek springs supplied water to settlers in 1840, after which the aquifer wellfields were developed in 1911. In 1933, the Avis Dam, with a capacity of 2.1 $Mm^3$, was developed and in 1954 water reuse was considered. By 1957, the aquifer was overused by 57 per cent. In 1958, the Goreangab Dam with a capacity of 3.6 $Mm^3$ was completed. Between 1964 and 1968 Windhoek city, in collaboration with the National Institute for Water Research and the Council for Scientific and Industrial Research in South Africa (at that time Namibia was administrated by the Republic of South Africa under a United Nations mandate), carried out research, including a pilot study, aimed at the direct potable reclamation of treated wastewater (Van der Walt, 2003). In 1968, while trying to overcome severe water shortages, this became a reality when the first reclamation facility started operations, producing high-quality water distributed for direct potable consumption. Ever since, the scheme has been successfully operated, encompassing a number of changes over the years. The original design has undergone a series of improvements (Van Rensburg, 2016; Wallmann et al., 2021).

**3-dam system – historical annual inflows (run-off) and storage over the past five decades**

The inflows into the 3-dam system are reflected in figure 5.10. The inflows into the dams are highly variable and erratic with no inflows to the Von Bach Dam in the 2012/13 season.

The run-off into the dams correlate well with the erratic rainfall. However, due to the varying characteristics of the catchment and intensity of rainfall, the correlations for each dam does not have a linear best fit for the rainfall/run-off graph. The droughts are not only severe but recurring (see figure 5.10). The yearly total inflows with a mean of 49 $Mm^3/a$ and median of 30 $Mm^3/a$ are far below the volumetric full supply capacities of the dam reservoirs. These drought situations require strong daily management of the available water, and involve every stakeholder in the strict management and crafting of sustainable adaptive solutions to meet the city's daily water demand.

Given that water from the Swakoppoort and Omatako dams is transferred to be stored in the Von Bach Dam, the water content in the Bach Dam over the years is indicative of the criticality of the water supply to CAN, especially Windhoek. The representative Von Bach storage content (see figure 5.11) over the years is indicative of the scarcity (dam frequently low in volumetric capacity) and unpredictable nature of Windhoek's water supply that require adaptive solutions and an all-inclusive stakeholder involvement to manage supply sustainably.

**Table 5.4: Characteristics of dams supplying water to Windhoek as part of CAN**

| Dam | | Omatako | Von Bach | Swakoppoort | Goreangab | Avis | Comments |
|---|---|---|---|---|---|---|---|
| **Parameter** | **Unit** | | | | | | |
| Elevation | MSL m | | | | 1585.31 | 1720 | |
| Catchment Area | km$^2$ | 5, 320 | 2,920 | 5,480 | 131 | 102 | |
| Mean Annual Runoff | Mm$^3$/a | 32.5 | 22 | 18 | | | |
| Full supply Capacity | Mm$^3$/a | 45.12 | 48.56 | 63.489 | 3.6 | 2.1 | |
| Storage Ratio | | 1.39 | 2.21 | 3.53 | | | Omatako fills in 1.4 rainy seasons while Swakoppoort requires 3.5 seasons to fill on average |
| Full Surface Area | km$^2$ | 15.545 | 4.884 | 7.808 | | | |
| Volume/Surface Area Ratio | m | 2.90 | 9.94 | 8.13 | | | Omatako is more of an evaporation pan |
| Dam Separate Yield 95% | Mm$^3$/a | 4 | 6.5 | 2 | | | |
| Optimised 3-dam Integrated System Yield 95% | Mm$^3$/a | 20 | | | | | when the dams are operated as an integrated system they yield more |

Source: Adapted from NamWater, 2021

NB: Goreangab and Avis Dams yield information was missing.

## 5.2.2. Water reclamation sources in Windhoek

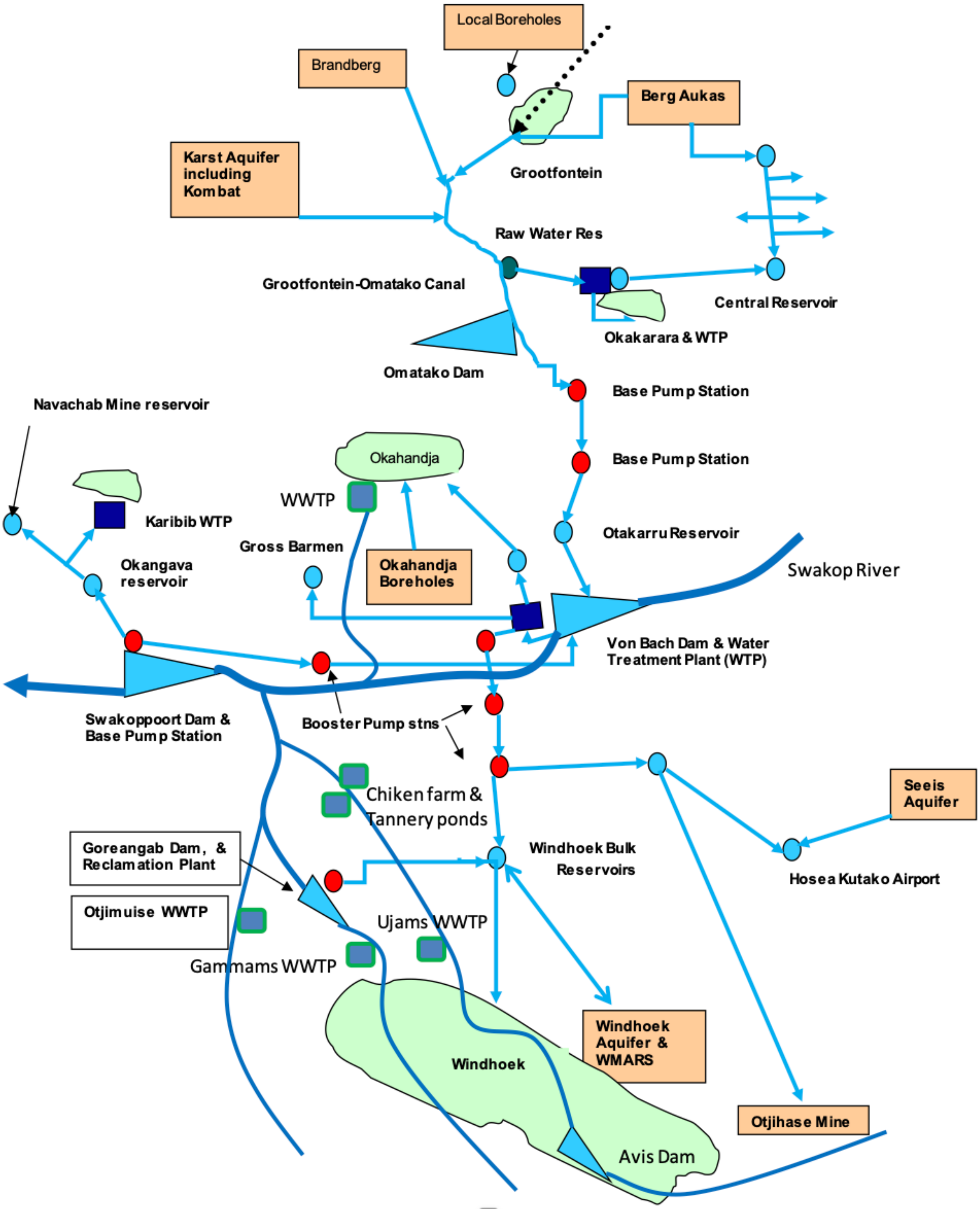
The Old Goreangab Water Reclamation Plant was commissioned in 1968. This wastewater reclamation (direct water reuse) plant was extended to 2.9 Mm$^3$/a over the next 30 years. The plant had a capacity of 3,300 m$^3$/day, which translates to 1.2 Mm$^3$/a. It was expanded to a 7,500 m$^3$/day capacity, which translates to 2.7Mm$^3$/a in 1997. The plant was originally used for drinking water. It has outlived its design life and now produces semi-purified water for the irrigation of the city's parks and gardens. At 1.3Mm$^3$/a, the plant's current output accounts for only 8 per cent of Windhoek's total water needs.

Windhoek's direct potable reclamation is based on diverting industrial and other potentially toxic wastewater (northern industrial areas) from the main domestic sewage system, which is treated at the Gammams Wastewater Treatment Plant. This is referred to as the non-treatment barrier strategy. The reclamation also prevents pollution by treating wastewater before it returns to the water system. The treated domestic effluent should be of adequate quality and consistent to meet the requirements of the raw water to the potable reclamation plant.

The multi-barrier (10 barriers) has been developed through extensive pilot and bench-scale research (Van Rensburg, 2016). Water treatment processes of the NGWRP are briefly described as in the next section.

The plant has a maximum raw water intake volume of 1,100 m$^3$/h. The water may be blended from the Gammams wastewater and water from the Goreangab Dam reservoir (usually the latter is left out because of poor water quality). Powder activated carbon is added to the raw water to remove dissolved organic carbon. The next process steps are pre-oxidation using ozone ($O_3$) and coagulation by adding ferric chloride ($FeCl_3$), which is then followed by flocculation where at times a polymer is added. This is followed by a dissolved air flotation (DAF) process where microscopic air bubbles are brought into contact with the flocculated water and the top thick scum layers are scrapped and removed. Caustic soda (NaOH) and potassium permanganate ($KMnO_4$) are added to the cleaner water to assist oxidation and precipitation of dissolved iron (Fe) and manganese (Mn) on the rapid dual media filters where

Figure 5.9: Schematic layout of CAN including Windhoek




Source: Adopted from Pazvakawambwa, 2018)

Notes: Some mines and aquifers are colour coded the same in instances where some of these disused mines are dewatered and become water sources.

Figure 5.10: Annual total inflow into the three dams (1970–2021)

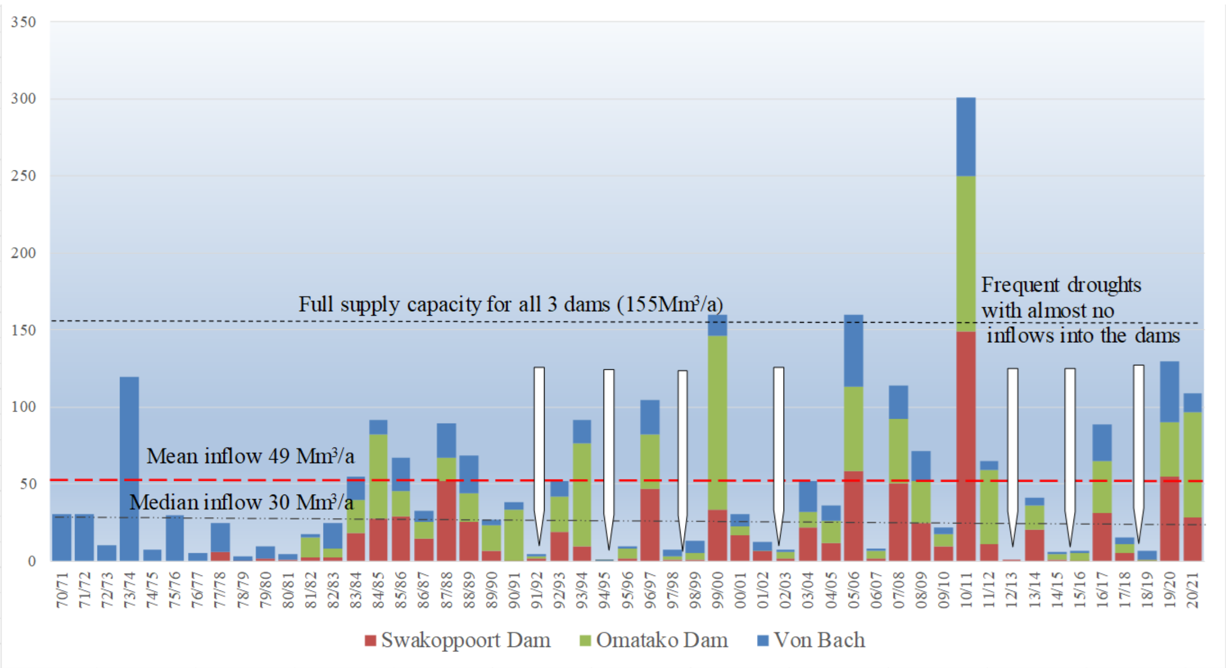
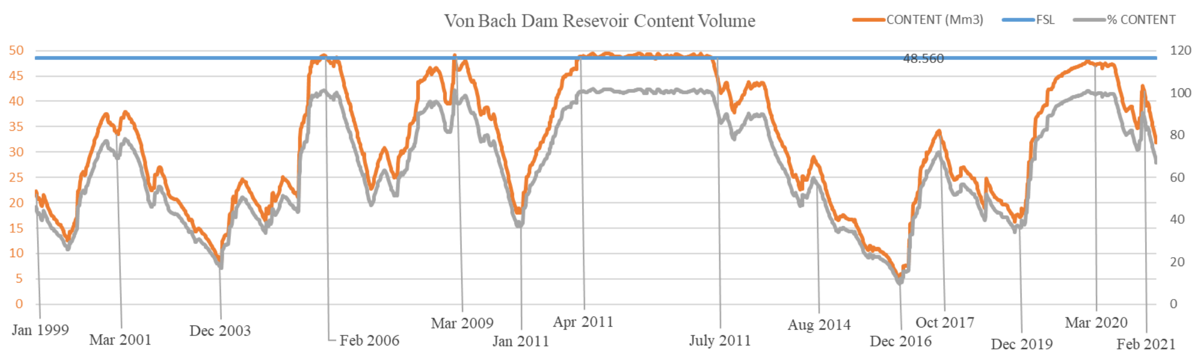



Figure 5.11: Von Bach Dam Reservoir content volume




Source: NamWater, 2021

all the suspended particles are removed. The filtrate is then passed through another ozonation process (93 per cent pure $O_3$) where organic compounds are oxidized and virus and parasites deactivated. Some hydrogen peroxide ($H_2O_2$) is added to remove residual ozone and protect the microorganisms in the next step, the biological activated carbon filtration. This filtration process is followed by the granular activated carbon adsorption stage where the remaining dissolved organic compounds are adsorbed to the granules. The next process is ultrafiltration where remaining pathogenic viruses and bacteria are eliminated and flushed out during backwashing. The potable water is then disinfected with chlorine ($Cl_2$) and stabilized with caustic soda (NaOH) to prevent corrosion of downstream potable water distribution infrastructure (Wingoc, 2021).

The maximum production capacity of NGWRP is 21 000m³/day (7.7Mm³/a) and the produced water is blended to the conventionally treated water in a pipe-to-pipe distribution network in a 25–75 per cent ratio (that is treated surface water -70 per cent plus groundwater -5 per cent).

Remarkably, the non-conventional direct potable reuse (DPR) plant in Windhoek does not incorporate reverse osmosis units (nonRO) and is different from indirect potable reuse practised in the United States and Australia. DPR does not require environmental buffers (groundwater replenishment or discharge to surface water reservoirs [Lahnsteiner et al. 2018]) as in these countries.

**Table 5.5: Comparison of some critical quality parameters of treated water from direct water reuse at NGWRP and conventionally treated water at VBWTP**

| Parameter | NGWRP | VBWTP |
|---|---|---|
| | | 50th Percentile |
| Turbidity NTU | 0.05 | 0.6 |
| aDOC, nDOC mg/L | 1.7 | 3.6 |
| UV254 | 0.015 | 0.05 |
| TDS mg/L | 871 | 161 |

According to the Windhoek Drought Response Plan (City of Windhoek, 2015) the drought crisis, as predicted by the CA Model, revealed that the available water supply in 2015 would extend for less than 12 months and forced water consumption restrictions imposed to save water by ± 23 per cent. The drought continued in 2016 and the Namibian president declared a water supply National Emergency in June 2016. The city increased reliance on reused water from 16–29 per cent during its 2015/16 drought (City of Windhoek, 2018).

Since 1968 there has not been any recorded disease outbreaks of the potable water produced from the reclaimed plant. See the comparison of water quality sample results from the DPR and the conventionally treated water at VBWTP in table 5.5. The cost of bulk potable water produced from DPR (N$11.19/$m^3$ or USD 0.78/$m^3$) is comparably cheaper than conventionally treated water (N$ 15.45/$m^3$ or USD 1.08/$m^3$) in 2015. The cost of bulk potable water produced from DPR could be cheaper due to proximity of both the raw water source (treated wastewater and distribution system within the city.

Wingoc is a water reuse company formed by the city of Windhoek, local and international firms, which is a success story of public-private-partnership water governance. By extending the public-private partnership-based arrangement of the Old Goreangab Water Reclamation Plant in 2002 and developing another new PPP on the NGWRP, it is a clear demonstration of satisfaction by both parties. This is confirmed by the Wingoc's current manager:

"On the PPP agreement between CoW and Wingoc, it is not on me to share details of the agreement. From my point of view, it is a successful partnership (CoW to confirm this statement) and the contract between the parties is very clear and detailed and the allocation of responsibilities and risks is clearly defined. The main theme of the agreement is transparency and sharing of information; to give an example we provide the CoW with (copies) of invoices of our suppliers, the financial part of the agreement is based on actual costs."

Given this experience, other cities can take a leaf on creating their own PPP arrangements to improve their water supply security.

### 5.2.3. Groundwater – Windhoek aquifer in the south of the city and northern brackish aquifer

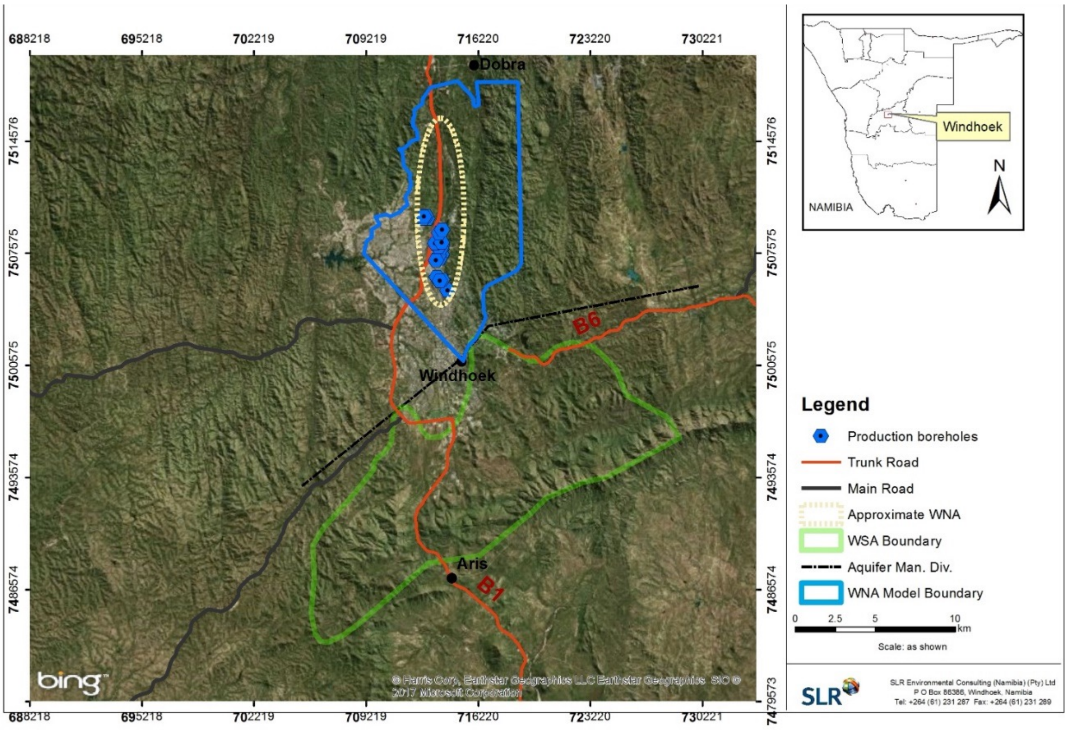
Groundwater is stored by the Windhoek Graben. The main fresh Windhoek aquifer is situated at the city's south, while the brackish aquifer is at its northern part (see figure 5.12). The main Windhoek fresh aquifer is at the city's southern and south-eastern parts, where the aquifer is being artificially recharged with treated water, and is referred to as the Windhoek Managed Aquifer Recharge Storage (WMARS).

#### Brackish northern Windhoek aquifer

The northern brackish aquifer, spanning from the Kuiseb Schist and alluvial along the Klein Windhoek River, was not seriously recognized as an essential groundwater source until the 2013–2019 dry spell and the 2015 drought that hit Windhoek. The Windhoek north aquifer is high in sulphates, fluorides, iron, chlorides and total dissolved solids. This northern aquifer situated in Elisenheim, Lafrenz, Northern Industrial Area and Brakwater is estimated to have a sustainable abstraction capacity of greater than 1.3 $Mm^3/a$ (see table 5.6).

The groundwater is considered to be from the precipitation recharge and subsurface flow from the

Figure 5.12: Windhoek aquifer in yellow and brackish Windhoek northern aquifer (WNA in blue; SLR, 2018)




## Table 5.6: Windhoek's wet industries permitted to abstract brackish water during drought periods

| Industry/Owner | Licensed Abstraction Rate ($m^3/a$) |
|---|---|
| Bokomo Foods | 24 090 |
| Namibia Breweries Limited | 766 500 |
| Namibia Construction | 87 600 |
| Nakara | 30 100 |
| NamPower | 221 760 |
| Coca Cola (Namibia Beverages) | 43 800 |
| Dynamic Concrete Solutions | 7 920 |
| Namib Mills | 60 000 |
| Avis Horse Stables | 4 000 |
| Meatco East | 107 050 |
| Namib Poultry Industries | Abstractions not confirmed |
| Total Allocated Abstraction Volume | 1 352 820 |

main southern Windhoek aquifer as well as from the Klein Windhoek River. These permitted groundwater abstractions supply water to wet industries during droughts (termed supply emergency periods of CAN) as was initiated since the 2015/2016 drought. During normal conditions, these wet industries rest their sources and deliver revenue to water service providers that can supply water from alternative sources. The wet industries abstract this brackish water and treat it with installed reverse osmosis treatment plants on their sites, should this be required. In issuing groundwater abstraction permits, MAWLR requires numeric groundwater models for any substantial abstractions as a way to manage the water levels and not to mine the aquifer.

### Main Windhoek aquifer and storage

Mostert (2017) indicated that Windhoek lies on the complex Damara Sequence geology group. Windhoek is underlain by the Kuiseb Schist, locally known as the "Windhoek Schist" and amphibolites (Biggs and Willems, 2001). While this type of geology does not possess the best aquifer properties because of low storage and infiltration levels, the metasediments of this sequence were thrust against these basement rocks and are overlying them. These metasediments consist mainly of pervious quartzites, micaceous quartzites. Thus, through complex geological processes associated with intracontinental rifting, continental convergence, orogenesis, and faulting including thrusting and rifting; the schists form the mountains in the south, east and west of Windhoek which is on top of the formed Graben aquifer (Christelis and Struckmeier, 2001; Zhang et al., 2004). Approximately 1.7 $Mm^3$ of naturally rechargeable groundwater can be extracted annually to add to Windhoek's water supply (Lafforgue & Lenouvel, 2015). Unfortunately, the amount of groundwater that can be used is limited and recharge is low. Windhoek makes use of artificial recharge methods allowing the city to store water for future use, thus reducing the recovery period and avoiding the exposure of the available 3-dam system surface water to evaporation (Mapani, 2008; Murray et al., 2018). The Windhoek acquifer is owned and operated by the city of Windhoek.

The fissility and fracture density of the schist indicate the vulnerability of the aquifer to pollution from the surface, hence the southern part of the city is a groundwater-controlled and protected area. All potentially risky developments are discouraged (Mapani, 2005).

**Windhoek aquifer storage and recovery capacity**

In a bid to top up the storage potential of the Windhoek acquifer and minimize evaporation, shallow and deep boreholes have been drilled to inject and abstract the water when required. Under the project of WMARS, Windhoek has developed ±37 production boreholes besides the additional monitoring ones. With Government funding (MAWLR, 2016), there are registered projects where the artificial recharge capacity is being increased from the present 2.8 $Mm^3$ in 2020 to a target value of 8 $Mm^3/a$ with the corresponding drought abstractions at 11.5 $Mm^3/a$ (without the hot water boreholes). In 2018, trials to test the aquifer registered abstraction rates of between 7.5 $Mm^3/a$ and 9.5 $Mm^3/a$. Higher abstraction capacities resulted in deterioration of water quality.

The WMARS project targets to abstract 19 $Mm^3/a$. The storage capacities of the aquifer depend on how deep the boreholes are drilled. It is estimated at 100 m deep slices, based on the 1950 water levels, the capacity of the aquifer is 41 $Mm^3$. This is quoted as the current storage that can be abstracted (Murray et al., 2018). It is estimated at 200 m deep slice that the storage is 61 $Mm^3$ and this is the forecast abstraction. The maximum storage abstraction potential is estimated at 71 $Mm^3$ at 300 m slice. However, with larger abstraction rates the water quality deteriorates and requires secondary treatment.

### 5.2.4. Existing and potential technologies

Among the multiple-drought adaptation and mitigation solutions employed by Windhoek, the stellar and highly technological Windhoek wastewater reclamation and direct potable reuse is outstanding. Windhoek has had its potable reuse technologies and innovations supported by research and continuous improvements. Between 1968 and 2002, OGWRP and NGWRP had five systematic continuous upgrades that were supported by collaborating local and international research. Due to the success of the operational NGWRP, a second direct potable reuse (DPR2) is under way. It is to be implemented by Windhoek after all stakeholders have endorsed the programme to be the city's immediate future medium-term potable water supply augmentation solution. However, extensive feasibility studies are ongoing to design the capacity of this plant, optimally, given that the raw water feed from the domestic sewage should be consistently adequate and of the same quality. Thus, this DPR2 requires Windhoek to upgrade its Gammams and Otjomuise Wastewater Treatment plants (City of Windhoek, 2021).

Similarly, technologies in groundwater are being advanced on the Windhoek-managed aquifer recharge (MAR). The injection and abstraction boreholes and aquifer storage water geohydrometric levels, were implemented with the support of Namibian geohydrological researchers and the Council for Scientific and Industrial Research (CSIR) of South Africa. Since the storage facility of the Windhoek aquifer has become of strategic importance to water security to the city, the establishment of the aquifer parameters and characteristics are ongoing to utilize the aquifer fully (City of Winhoek, 2021). The introduction of artificial recharging and the use of this aquifer storage to evade evaporation losses are significant technological strides that are implemented by the city.

NamWater and the city also make use of available technology on bulk water metering and water quality measurements. They use real time telemetry and Supervisory Control and Data Acquisition software to comply with standards and immediately correct any anomaly. The hydrometric rainfall network measurements and recording around the Windhoek and the 3-dam system is based on automated rain gauges whose records are collected via telemetry and managed on supervisory control and data acquisition (also called SCADA).

Windhoek and NamWater have implemented prepaid metering of potable water supply at household level experimentally. A section of the informal settlement where the city has installed prepaid meters has maintenance challenges, resulting in less enthusiasm for further implementation of prepaid meters. On the other hand, NamWater has been installing bulk prepaid meters on the supply of other local authorities that owe billed debts to NamWater. Thus, prepaid meters are being used as debt recovery and management tools. However, this tool has not been applicable to Windhoek as its bulk water payments to NamWater are always up-to-date.

### 5.2.5. Infrastructure upgrades and extensions

Water leakage usually reflects old infrastructure that is nearing or beyond its design lifespan, or a lack of maintenance. The Windhoek Bulk Water Master Plan (City of Windhoek, 2004) indicated that leakage rates in some households were very high due to inferior equipment and lack of maintenance. The leakage on the premises had an average of 88 litres a day. While the acceptable leakage could have been around 20 l/d. Thus, the city implemented a continuous non-revenue water reduction programme, which resulted in the total current water losses, estimated at 12 per cent (City of Windhoek, 2021).

Water delivery infrastructure of the potable bulk water supply and distribution network as well as the wastewater collection network are continuously upgraded and extended to new development areas. The rehabilitation of water schemes is guided by rigorous water resources and infrastructure planning by the city, NamWater and Wingoc. The drilling and connection of additional boreholes as well as establishing WMARS require high capital input by the city. Usually, these development funds have to be sought locally and internationally. The VBWTP to Windhoek bulk pipeline is due for upgrade. NamWater upgraded the pump stations on this pipeline in 2014. The existing pipelines that transfer potable water between VBWTP and Windhoek were deemed inadequate in a study carried out in 2018 (City of Windhoek, 2021). The existing 1,100 mm pre-stressed concrete pipeline is more than 40 years old and was proposed to be replaced with a 1,400 mm diameter pipeline to accommodate the increasing water demand of Windhoek.

Thus, the capacity of this pipeline has been resiliently increased despite it having reached the end of its design life. The Ujams industrial wastewater treatment plant, was upgraded in 2015 by the city of Windhoek on a PPP arrangement to avert the industrial pollution threat to the downstream Swakoppoort Dam reservoir, one of the three strategic supply dams to Windhoek. For the next 21 years, the 5,000 $m^3$/day capacity Ujams plant will be run by Ujams Wastewater Treatment Company, a special purpose vehicle company that is using high technology membrane bioreactor for the treatment of the wastewater. It is interesting to note that the treated effluent may gain potential to be utilized by an upcoming mine establishing 100 km outside Windhoek for the purpose of iron ore processing.

## 5.3. WATER DEMAND

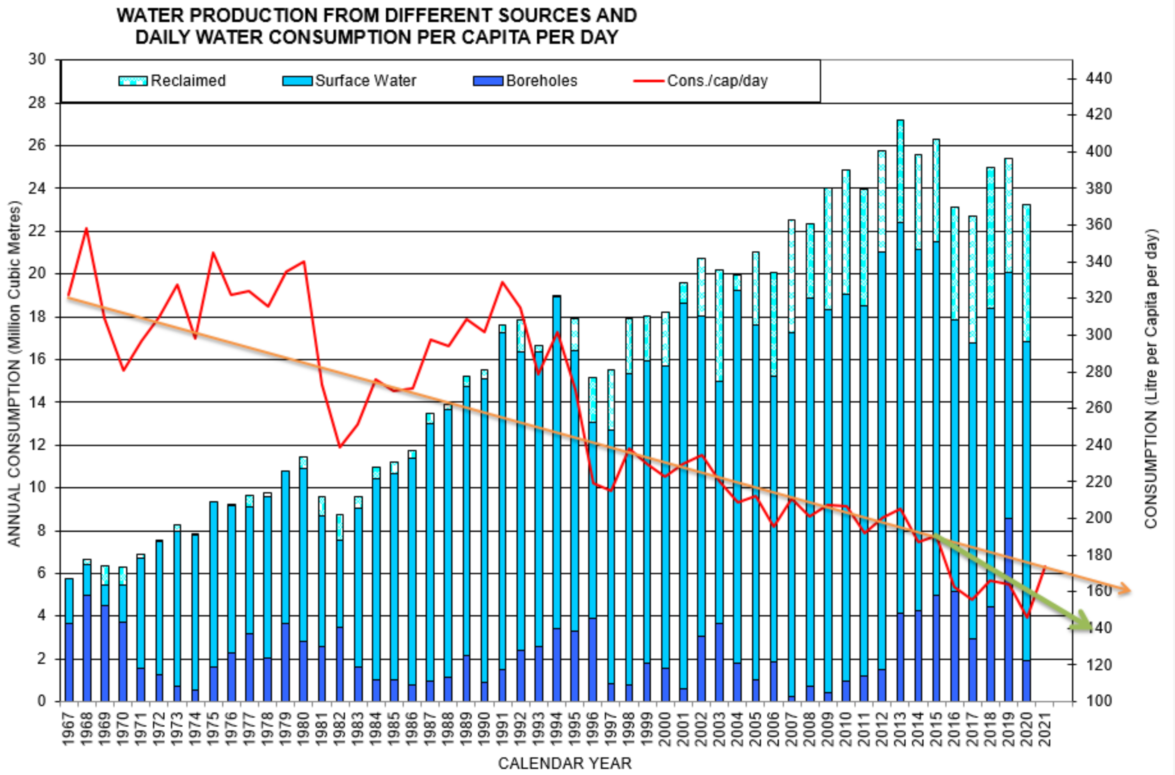
### 5.3.1. Historical water demand and adequacy of sources

Windhoek's water sales represents the production of this natural compound from various sources in the city only as a proxy for demand. The annual sales demand for Windhoek ranged between 22 $Mm^3$/a and 27.2 $Mm^3$/a in the last nine years. The peak was in 2013, depending on the availability and severity of the frequent droughts as reflected by decreasing per capita consumption when there is water scarcity and water saving strategies by the city (see figure 5.13). The per capita consumption decreased from ±320 L/cap.d in the late 1960s to ±160 L/cap.d in 2021.

The capacity of the developed sources supplying CAN is quoted at threshold upper limit of 32–35 $Mm^3$/a (Bruce and Burger, 2019). This capacity includes the 95 per cent safe yield of the combined 3-dam system quoted at 20 $Mm^3$/a. However, the actual yield of the sources, as reflected by frequent inadequate annual inflows into the dams, is far less than the threshold limit. This means that for sustainable water supply to Windhoek and the rest of CAN, the sources have been surpassed by the water demands of the population.

The real value of the Windhoek Managed Aquifer Recharge Scheme is not reflected in figure 5.13. The analysis above depicts only the long-term natural sustainable recharge and related abstraction of the Windhoek aquifer quoted at 1.73 $Mm^3$/a. High rates of groundwater abstraction, based on conjunctive use of groundwater are much greater than the rates of natural recharge. Higher emergency volumes have been abstracted from the Windhoek aquifer as well as from the Karst area aquifers near Grootfontein during drought periods to limit shortfalls. In the case of the Windhoek aquifer, which is used as a "water bank", this water needs to be replenished in order to be available in the future. Total water production or supply, including semi-purified water, reached a peak of 28.817 $Mm^3$/a (27.216 Mm3/a potable consumption) in 2013.

Figure 5.13: Historical water demand of Windhoek




Data source: City of Windhoek

## 5.3.2. Projected water demand

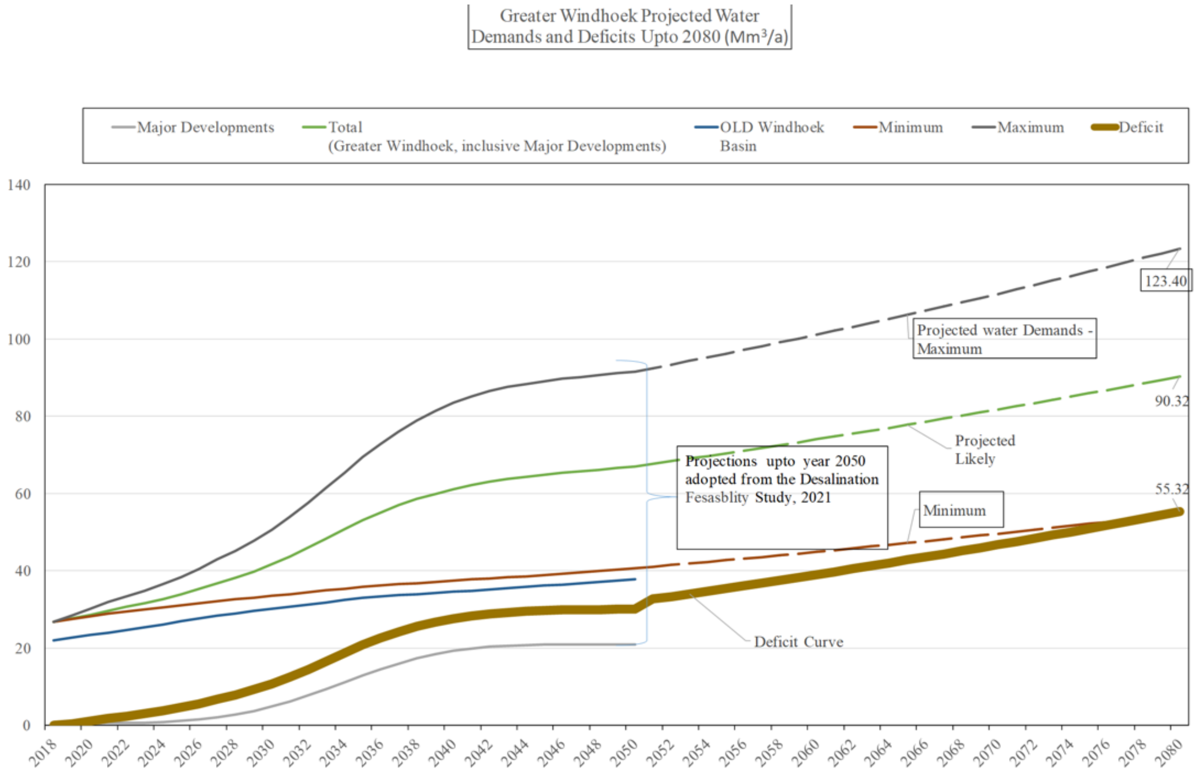
Water demand projection is complex as it requires knowledge of the drivers. There is also need to strike a balance  between the two to avoid overestimation or underestimation of the expected water demands in future. Overestimation results in unnecessary capital expenditure of oversized infrastructure, whose costs cannot be recovered from the end-user tariffs. Windhoek, NamWater and MAWLR prefer the demand-orientated augmentation to supply-orientated approach to avoid the undue capital expenditure, given that NamWater was constituted on a cost-recovery operational basis. Reclamation and water demand management measures are also considered when computing the water demand deficits and assessing water demand projections The projected demands for Windhoek are indicated in figure 5.14.

From year 2018 to 2050, water demand projections to supply Windhoek in future mirrored those used for the Desalination Feasibility Study (NamWater, 2021) based on various growth factors, population growth and existing trends for domestic and industrial water demands. Thereafter, moderate water demand growth rates of 2 per cent were applied in computing the water demand projections between 2050 and 2080. The projections indicate water demand deficit of Windhoek of 30 $Mm^3/a$ in 2050. Based on this figure, the likely total water demand of Windhoek in 2080 was projected to be 90 $Mm^3/a$, with a corresponding deficit of 55 $Mm^3/a$.

## 5.3.3. Water demand by sectors in Windhoek

In assessing the baseline demands and projecting the future water demands it is noteworthy that water usage by the industrial and domestic sectors in Windhoek vary yearly depending on the prevailing drought status (see figure 5.15). A considerable number of manufacturing firms in Namibia are in Windhoek. In a report covering 2015 through 2016, the Namibia Manufacturing Association said at least 300 of the total 500 manufacturing firms in Namibia were in Windhoek. On the domestic water use, the distribution of population of each income group and per capita water consumption was estimated as shown in table 5.7. There are huge disparities in the water consumption per capita, per day.

Figure 5.14: Windhoek's projected water demand and deficits up to year 2080




Source: NamWater, 2021

## Table 5.7: Distribution of Windhoek's population (2006) and per capita consumption (2010)

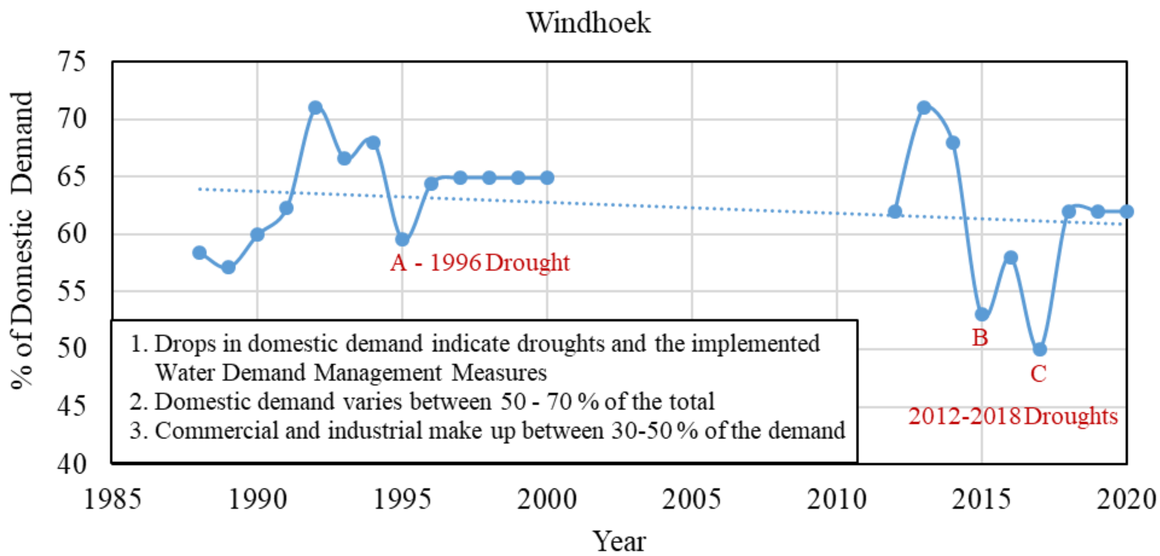
| Settlement Income Group | Population Distribution in 2006 (%) | Water Consumption (L/Cap.d) in 2010 |
|---|---|---|
| Informal Settlement | 27.6 | 27 |
| Low income | 30.6 | 188 |
| Middle income | 14.7 | 252 |
| High Income | 12.4 | 306 |

Source: Adopted from Uhlendahl et al., 2010

### 5.3.4. Existing water tariffs

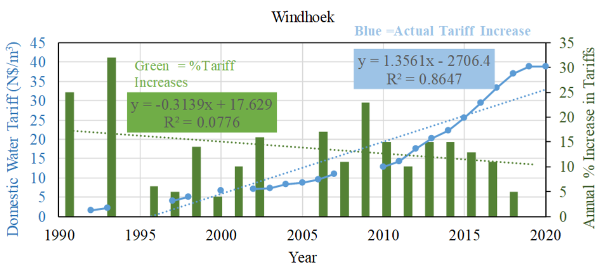
The historical tariffs for Windhoek are presented in figure 5.16 and subsequent notes. While Windhoek's domestic tariffs are not necessarily ring-fenced on the water supply provision services, it is evident that the block tariffs had high frequency of being reviewed, with almost yearly increases that reflected consciousness on the part of the key stakeholders of the need to keep abreast with cost recovery, viability and affordability issues.

Figure 5.15: Windhoek's water usage by sector




Source: City of Windhoek, 2021

Figure 5.16: Historical and present Windhoek potable water tariffs




Notes:

1. Water tariffs have been increasing over the years to compensate for inflation, increasing water supply service requirements and as a tool for water demand management.
2. The annual percentage increase in tariffs have been in the range of 5–32 per cent.
3. With the related success of reduced demand per capita (reduced from 315 L/cap.d in 1992 to 140–160 L/cap.d in 2020), the decreasing trend in the annual increase in tariffs could imply reaching the inelastic demand phases.

Source: City of Windhoek, 2021

## 5.3.5. Ongoing multiple water sources mix strategy - intervention

The water demand of Windhoek has nearly surpassed the developed supply sources (NamWater, 2021) as indicated in figures 5.13, 5.14 and table 5.1. Two strategic approaches have been applied to augment the drinking water supplies in Windhoek. One approach is to embark on the "management solution". This solution includes implementing water demand management measures as well as embarking on initiatives that optimize and enhance water reuse, the three integrated dams, and conjunctively water banking into and abstraction from WMARS. Other complementary initiatives reduce and control water pollution by upgrading of wastewater treatment plants (Otjomuise, Gammams, Ujams) to prevent further pollution of the Swakoppoort Dam (Pazvakawambwa, 2018).

The second approach is the supply-oriented "resources solution". This approach acknowledges that the developed water resources supplying CAN are already strained to meet current demand and would need augmentation from new additional sources to meet Windhoek's future projected water demands. Therefore, CAN may have to be linked to the sustainable water sources that could include the perennial Okavango River basin transfer source and desalinated water from the Atlantic Coast.

The resilient existing water supply strategy deployed by Windhoek, NamWater, MAWLR, industrial and wastewater and water reuse PPP companies include using a mix of multiple sources. The Multiple-Sources Mix Strategy includes surface water sources (3-dam system); groundwater sources; direct reclaimed water reuse; water demand management measures and artificially recharged Windhoek managed aquifer. NamWater and Windhoek, on weekly and yearly basis, jointly monitor and review these sources against set water demand targets. The city's water supply security strategies has for long been on a short-to-medium term basis (weekly, monthly, yearly planning, monitoring and management). Despite the absence of sustainable long-term developed of sources in recent years, the successful reviewing, replanning and efficient use of available developed sources in an all-inclusive stakeholder transparent approach has been a remarkable achievement as elaborated in the following paragraphs.

### 5.3.6. Regular short-term water supply security strategies for Windhoek

#### Run dry date CA-Modelling

NamWater runs a hydrological/planning and water-use and balance model (called the cellular automata (CA) Model). The model takes into consideration all the water sources (including the 3-dam system) and all water users' demand within the CAN integrated water supply area. The model then assists in simulating the extent to which these available water sources and existing infrastructure can stretch to supply water to CAN (including Windhoek). The short-term, worst-case scenario is modelled assuming that the three integrated dams do not receive any inflow within the next two or three rain seasons (referred to as "run dry date"). The model's worst-case scenarios and their proposed mixed target water demand management measures are presented during each of CAN's annual stakeholder workshop at the end of each rainfall season. The most optimal scenario is then adopted for that particular year for implementation. Monitoring of the dams' drawdown, groundwater levels and potable water production as well as water consumed by each user in the CAN integrated system is carried out and compared with set water demand targets to be upheld until the next CAN workshop. NamWater and Windhoek hold bi-weekly meetings of their working teams to monitor the set water demand and quality targets. Should there be non-compliance with the set targets, then appropriate actions are agreed on to make the needed adjustments to the annual targets. There are bi-weekly monitoring assessments and report back analysis and summary. The emphasis is on open channel communication and exchange of information, team planning and inter-departmental (NamWater, City of Windhoek, Wingoc, MAWLR) discussions and meetings are usually held.

Unlike the "run dry date" CA modelling, the medium-term and long-term water supply solutions assume the 3-dam system will receive run-off inflows that are stochastically determined.

#### Windhoek's water demand management measures

A severe drought in 1993 caused a number of people to relocate to Windhoek. Confronted with these two twin pressures on its water supply, the city decided that the best way to conserve water in the short and medium terms was through water demand management. Accordingly, an integrated Water Development Management (WDM) policy was initiated in 1994. Its aim was to reduce consumption and improve water use efficiency, especially within the high-income group, by implementing a wide range of measures. The strategy consists of policy issues (including block tariffs), public awareness campaigns, and technical measures.

One of the most effective measures carried out to control water consumption was through the block tariff structure, whereby the price of water increases with the volume used. Between 1991 and 1997, residential water use decreased substantially from 330 to 220 L/cap.d (see figure 5.13). The decrease was attributable partly to the new pricing policy (van der Merwe, 1999).

Initially, the block tariff structure reduced water consumption by changing consumers' water use habits, and savings exceeding 30 per cent were achieved (van der Merwe 1999). However, over time, water use per capita more or less reached a plateau, despite water rates increasing almost yearly, signifying some inelasticity of demand. During another drought in 2015, Windhoek introduced a new "penalty tariff" for individual households that consumed more than 50 m$^3$/month. The threshold was lowered subsequently to 40 m$^3$ and residents' basic water tariffs were increased by 10 per cent in 2016 (Haidula, 2015; Van Rensburg, 2020; see also figure 5.13).

### Table 5.8: Windhoek's drought severity indicators since 2015

| Water Supply (month of water available) | >30 | <30 | <24 | <18 | <12 |
|---|---|---|---|---|---|
| Water Availability Status | Normal | Water Scarcity (1) | Drought (2) | Severe Drought (3) | Water Crisis (4) |
| Water Use | Baseline Consumption | Reduced Water Consumption | Water Savings | Increased % Water Savings | Restrictions |
| Programme Implementation | Do not waste water | Drought Watch; Increased communication on dry conditions and Drought Response Committee | Mandatory water saving restrictions | Water savings required (prohibits lawn watering) | Rationing- water supply for essential uses |

Windhoek's implementation of the WDM policy is seen by many as a success story (van der Merwe 1999; Magnusson 2005; Van Rensburg, 2020). The success can be attributed to the dedication, adaptive, robust management and good water governance; the holistic approach and public-private water saving initiative and campaigns.

However, in spite of this progress, the low-budget allocation and inconsistency in implementing the water infrastructural plan affected it negatively. There is strong motivation only during severe droughts and not when water levels are considered sufficient.

The adaptive and mitigation water demand measures by Windhoek are exemplified and summarized in the Drought Response (2015–2016) and Water Management Plan (2019) documents. These drought response frameworks started to be developed in the 1990s and with progressive drought experiences, they have been improved.

### Drought Response Plan (City of Windhoek 2015/16)

Guidelines outlined in a Drought Response Plan are intended to provide a framework for timely drought response while maintaining flexibility to respond to unique drought conditions. The plan (see table 5.8) consists of (1) drought severity indicators, (2) response actions, and (3) response programme elements (Van Rensburg & Tortajada, 2021).

Drought severity indicators are a variety of factors that should be considered in choosing an appropriate drought response. The indicators are based on the CAN Annual Workshop Analysis and adopted recommendations. The four stages of drought severity are:

1. Water scarcity (conditions requiring public awareness to avoid water wastage).
2. Dry to severely dry drought (imposes mandatory watering restrictions and requires effort on the part of customers).
3. Severely dry drought (imposes compulsory water savings on Windhoek's customers and will likely result in damage to or loss of landscapes, prohibiting lawn watering).
4. Exceptionally dry and insufficient water crisis (activates a rationing programme where no outdoor watering will be allowed and indoor water use will be restricted).

Drought impact factors include the socioeconomic impacts and indicators, the CAN working team assessment, media and political response, environmental effects and the uncertainty associated with forecasts.

Additionally, drought response programme elements are guidelines for water use during different levels of drought. The drought response programme section indicates how the drought severity indicators align with the suggested drought response framework. In short, it is a guide to water users under the various levels of drought restrictions. The drought reesponse programme advises on outdoor watering and irrigation, equipment, washing events, recreational water features, commercial/industrial processes and any amendments to the Tariff and Community Awareness programme. These efforts can be summarized as follows:

**Table 5.9: Windhoek's domestic water block tariffs (2016) as an effective tool for WDM measures**

| Metered Household Water Consumption ($m^3$/ day) | Metered Household Water Consumption ($m^3$/ month) | Non-Drought Period Tariff per N$/$m^3$ | Total Cost (N$) |
|---|---|---|---|
| 0–0.2 | 0–6 | 17.11 | 0–106.62 |
| 0.201–1.333 | 6–40 | 26.47 | 107–1 058.8 |
| 1.334–1.666 | 40–50 | 48.82 | 1 059–2 441 |
| >1.666 | >50 | 112.5 | >5 625 |
| | | Drought period with limited water available Tariff per N$/$m^3$ | Total Cost (N$) |
| 0–0.2 | 0–6 | 17.11 | 0–106.62 |
| 0.201–1 | 6–30 | 26.47 | 107–794.1 |
| 1.01–1.333 | 30–40 | 48.82 | 795–1952.8 |
| >1.333 | >40 | 112.5 | > 4500 |

1. Setting and increasing water-saving targets through the Central Area Committee (driven by NamWater)

2. Progressive increase of water tariffs charged to consumers

3. Targeted water saving initiatives with industries and other key stakeholders

4. Identifying and targeting high water consumers

5. Rapidly financing and implementing emergency abstraction from the Windhoek aquifer

6. Increasing water supply from other sources.

An example of Windhoek's block tariffs (2016) that were punitive for higher water users as presented in table 5.9.

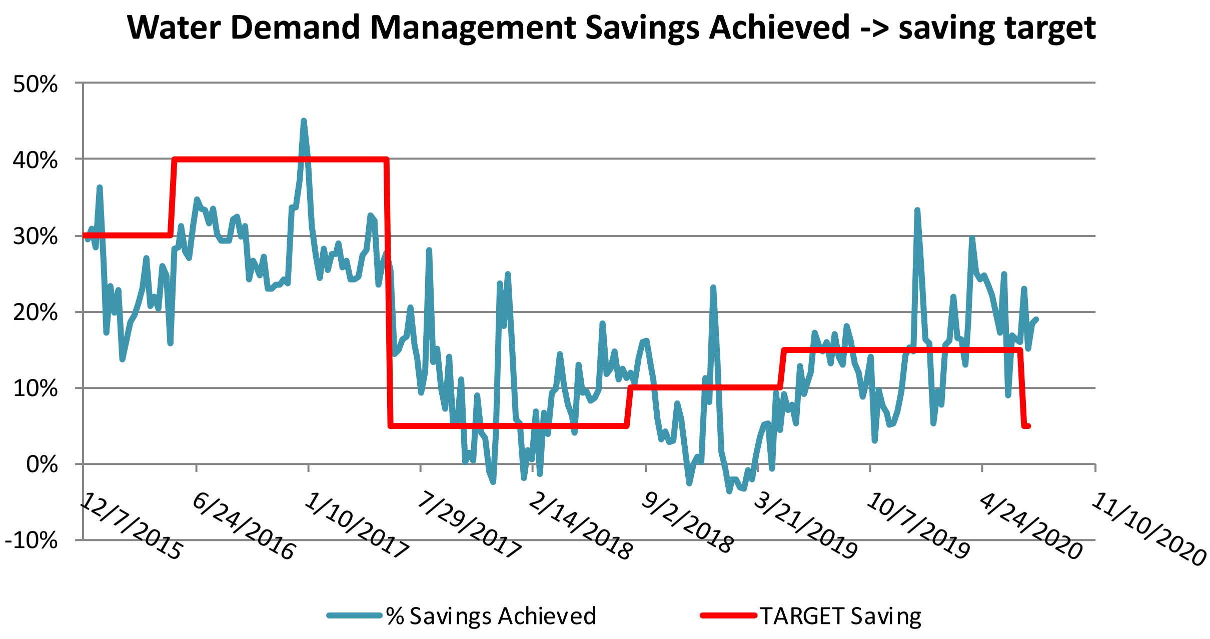
Table 5.6 demonstrates how the water price per cubic metre increases during times when available water is limited. After the first block, the water price goes up by about 45 per cent per block (see table 5.6). Businesses have a flat tariff as Windhoek realizes the importance of businesses and that restricting water usage during times of limited water availability could influence the performance of a business. The cost of semi-purified water is cheaper for municipal consumers than the normal block tariff. This encourages people to supplement some of their fresh water use with semi-purified water, increasing the fresh-water storage savings for future needs (van Rensburg, 2016).

The negative effect of placing economic value on water is that the lower-income groups suffer under the tariffs, if not calculated correctly. In Windhoek, there are a number of low-income (informal settlements) areas, including Katutura, Khomasdal and Otjomuise. Windhoek tries to implement affordable tariffs to decrease water tariffs for these low-income areas.

**Water Management Plan (City of Windhoek, 2019)**

Similarly, guidelines outlined in the Water Management Plan are intended to provide a framework for continuous water management and timely drought response while maintaining flexibility to respond to unique water supply challenges. It is important to note that water demand management cannot be applied only during times of droughts as the required response heavily relies on public support, which takes time to acquire. Windhoek uses this plan to manage water supply and water use during varying supply situations (see figure 5.17). The Water Management Plan consists of supply situation indicators, WDM response actions and WDM programme elements.

Figure 5.17: Historical water demand management savings achieved by Windhoek (2021)




Supply situation indicators are varying supply scenarios as announced by NamWater through the use of the CA model. Dam levels at the end of a rainy season are at the bottom-line factors affecting supply, including weather, precipitation, run-off, evaporation, collection system limitations and water use. Supply situation indicators will be based on the results obtained from the CA model. This provides an indication of the period for which water is available to sustain the present demand given available resources at varying rates of utilization. The six categories of likely supply scenarios in descending order (A+ to E) include: best, normal, water alert, scarcity, severe scarcity, and water crisis. Subsequently, WDM response actions are guidelines for managing water demand according to varying supply situations. The six supply scenarios categories match a five-stage WDM categorization. During a "best/normal" situation consumer awareness is maintained and realistic demand monitored; a "supply/water alert" classification requires increased communication on supply conditions; the rest of the categories are similar to the Drought Response Plan. The WDM Response Index and WDM programme provide public awareness to avoid water wastage and achieve minimal targeted savings (see figure 5.17).

The Water Demand Management Programme indicates how the supply situation indicators align with the suggested water demand management response framework. It also guides water users under various levels of supply scarcity. The WDM programme advises on outdoor watering and irrigation, equipment washing events, recreational water features, commercial and industrial processes and any amendments to the Tariff and Community Awareness Programme.

### 5.3.7. Historical medium- to long-term water supply sources for Windhoek

Water supply to Windhoek, given the city's semi-arid nature, erratic rainfall patterns and vulnerability to climate change, presents the most interesting case study. Various past and recent bulk water studies are presented in the next sections and table 5.10.

The master plans indicated in table 5.10 and housed by NamWater as well as Windhoek's in-house on-going city integrated masterplan; the Master Wastewater Infrastructure Plan to secure long-term water solutions have not materialized in any recent long-term solution. However, short- to medium-term solutions have managed to save the desperate situation of supplying Windhoek with potable water. These short to medium term initiatives include Water Demand Management, the dual pipe system for the distribution of semi-purified sewage for irrigation, sustainable reclaimed potable water from domestic sewage, aquifer recharge and storage as emphasized and proposed in the 2019 – Medium-Term Water Supply Alternatives for the Central Area of Namibia.

### Table 5.10: Summary of long-term master plans to supply Windhoek and CAN

| Plans | Options considered | Next Preferred Options |
|---|---|---|
| 1973 Water Master Plans | Groundwater; desalinated water from the Atlantic Coast and linking supply from Okavango | Okavango River link water supply |
| 1993 Water Master Plans | Same as in 1973 and added environmental impact issues | Okavango River link water supply |
| 1995 Central Area Water Master Plan Interim Phase | This plan included stochastic modelling of the sources and the optimisation of the Okavango Link Project | Okavango River link water supply. |
| 1997 Feasibility study on the Okavango-Grootfontein link (WTC 1997) | Water supply from the perennial Kunene and Orange Okavango rivers as well as supply from the desalination option<br><br>Study was prompted by 1996/97 drought rainfall/run-off season | The Okavango option was preferred due to favourable lower cost. Four years later, another study was conducted. |
| 1996- 1998 NGWRP studies by CoW | Water supply from wastewater direct potable reuse upgrade and replacement of OGWRP | NGWRP preferred implemented under PPP arrangement in 2002. |
| 2001 Central Area System Update | Study entailed the Central Area (CA) model with time series analysis for the Windhoek water demands and available sources. The analysis defined the failure of supply as that level of shortfall with 12–15 per cent reduction of demand. | Recommendations adopted and implemented. |
| 2004 Feasibility study on water augmentation to the Central Area of Namibia | Study entailed update of the CA model; recommended artificial recharging of the Windhoek aquifer (WA) after comparing it with the Tsumeb and Karst Area III aquifers as well as comparing it with the Okavango Link option. | The artificial recharge of the (WA) being implemented in conjunction with the drilling deep well (for both injection and abstraction of this aquifer; and protection of the acquifer from the risk of pollution. |
| 2011 NamWater Bulk Water Masterplan | NamWater develop the Combat Mine scheme to avoid over-abstraction of the Berg Aukas mine groundwater scheme; replacement of the Von Bach Water Treatment Plant to Windhoek Pipeline. Pump stations were then successfully replaced in 2014; improvement of polluted raw water quality of Swakoppoort Dam Reservoir by proposing retrofitting a DAF treatment process and catchment management. | The plans were adopted as medium-term interim solution and implemented except for the DAF system. Note that the Central Area water balance model of water sources predicted shortfall starting in 2013. |
| 2011–2016 Pre-Feasibility Study on the Augmentation of Water Supply to the Central Area of Namibia and the Cuvelai | Study recommended improved water use efficiency of the VBWTP and Swakoppoort Dam Water Transfers by reducing their treatment losses; water demand management measures and fully utilize the Goblenz aquifer boreholes as medium-term solutions. Reclamation of Windhoek's wastewater was considered for medium term. Okavango River Link project and desalination option were considered for long term. | The plans were adopted as medium-term. The second wastewater reclamation plant's feasibility study under way in 2021. |

### 5.3.8. Future Medium-Term Water Supply Sources for Windhoek (NamWater, 2021) under Development

In the medium term, Windhoek plans to keep all the borehole areas of its aquifer including use of the hot borehole water left on the supply mix. This is to avoid the risk that would be posed to the water supply infrastructure if this measure is not taken.

By harnessing all boreholes not currently in use, an additional ±1.5 $Mm^3/a$ in Windhoek could be utilized. Equally, farther north to the northern aquifers 40 to 50 km north of Grootfotein, the proposed Abenab aquifer scheme is to be abstracted and supply CAN up to Windhoek. This groundwater scheme is being funded by the Government and loans from the African Development Bank. The scheme is projected to supply 12 $Mm^3/a$ in three consecutive years and then will be rested for 12 years to recharge the aquifer sustainably.

Top on the list of the medium-term water supply augmentation to Windhoek actions is the Direct Potable Reuse Plant 2 (DPR2) whose feasibility study is ongoing to facilitate capacity sizing and informed implementation. The KfW (German development bank) has pledged funding loans to this scheme that will also see the upgrading of the upstream Gammams Water Care Works, a domestic wastewater treatment plant.

The extension of the Windhoek Artificial Recharge scheme is also top priority for the city to utilize the Windhoek aquifer and its storage. Windhoek carried out a feasibility study that was funded by KfW and the United Nations Development Programme, and the Development Bank of Southern Africa assisted in putting the proposal to the Green Climate Fund. The response was that the project would get the major proportion funded as a loan to Windhoek. This could be a potential source of funding for the project if the city meets these requirements.

The almost unused 3.6 $Mm^3$ capacity Goreangab Dam reservoir, though not on the city's priority list, can be utilized when its water is treated by installing a reverse osmosis treatment process as proposed by Pazvakawambwa (2018). It is also important to note that more than 30 option sources were assessed to augment CAN and Windhoek in the medium term (Medium-Term Water Supply Solutions to the CAN, (NamWater, 2021)

### 5.3.9. Proposed long-term water schemes for Windhoek: Okavango River Water Source and Desalination Options (NamWater, 2021)

The recently completed *Feasibility Study for the Desalination Plant and Water Carriage System to Secure Water Supply to the Central Coast, Windhoek and En Route Users (2021)* had an option of supplying Windhoek with desalinated water. The study outcome was that the scheme would utilize a hybrid of renewable solar photovoltaics energy and grid power. The bulk cost of the desalinated water when conveyed to Windhoek was not likely to be affordable as it would be seven times the cost being charged now to the city. The project is not shelved yet as it is still to be compared on the same parameters with supply of water from the Okavango Link or supply from the recently completed Nackartal and Hardap Dams in southern Namibia. The feasibility study recommendations were to carry out the optimization of the Okavango Water Supply Option as well as the Southern dams' supply option and their comparison with desalination feasibility study results in a bid to conclude long-term water supply to CAN (mainly Windhoek). It should be realized that the Okavango River is transboundary and whose environmental and social impact assessment should meet the RAMSAR Convention procedures as it affects the Okavango Delta downstream.

In summary, for the long-term water security of Windhoek, more studies are currently being carried out.

### Funding constraints of water supply infrastructure for cities vulnerable to climate change

Despite financial cost recovery being pursued by Windhoek and the national bulk water supplier, NamWater, the case study reveals that Windhoek requires considerable capital funding to implement short- to medium-term initiatives to ensure sustainable water supply. The outstanding implementation of long-term water supply initiatives for the city requires enormous capital inputs that it should secure to ensure supplies are sustainable. These long-term sources are expensive, unaffordable to the city's low-income groups; for instance, the undeveloped distant sources like the desalinated water from the Atlantic Coast. These high-capital requirements leave water-stressed, drought-prone cities like Windhoek increasingly vulnerable to the effects of climate change. While the Green Climate Fund is a targeted solution to this challenge, Windhoek's experience may reveal, according to the author, long processes on critical transformative climate projects.

It should be noted that the real and critical transformative climate projects require huge capital input and by their nature are less bankable. It is for this reason, perhaps, that many vulnerable cities have not implemented sustainable solutions to the impacts of climate change. Thus, to de-risk these projects, funding should be more accessible and allow easy credit facilities by ring-fencing the projects. Credit worthiness should be on the project rather than the institutions applying the project funds. Positively, the Green Climate Fund shows real special concessions. However, vulnerable cities to climate change may be equally financially stressed to pass the screening of credit worthiness for high-capital funds. While climate changes such as increasing global temperatures, more rainfall and run-off variability and likelihood of severe flooding as well as droughts are slowly closing in all around the world, their impacts are already fast-affecting arid and semi-arid cities. Unless capital funding is easily accessible and "friendly", these cities may have a legacy of accelerated constraints on their water supply systems heightening water supply insecurity and ensuring continuous poverty.

## 5.4. CONCLUSIONS AND RECOMMENDATIONS

The challenges of Windhoek have been water scarcity and long droughts. Rising demand for water has been caused by increasing population growth, accelerated by rural-urban migration. This has also resulted in more than 30 per cent of the city's population consisting of informal settlers putting pressure on the outgrown formal water supply system. There are also water pollution problems originating from the city to downstream dam reservoirs that the Basin Management Committee is trying to correct.

The developed water sources for the city are being overtaken by existing and projected water demands, leaving only distant and costly sources as future water supply solutions. However, the looming climate change challenges make existing and future sources vulnerable if such sources are climate change variant. The uncertainty of the nature of climate changes affecting surface and groundwater sources makes planning even more difficult. In summary, according to the Namibia Climate Change Vulnerability and Adaptation Assessment, it is not obvious whether or not the amount of rainfall in Namibia will be reduced, although intensity is likely to remain the key aspect of Nambia's climate in the future.

Despite the scarcity and aridity of Windhoek, sustainable water supply in the short term has been historically achieved. Every drop of water and every stakeholder counts in the city's planning and implementation strategies to secure supplies. Multiple-source uses and adaptive strategies, including water reuse added to the success mix.

The greatest political will and support has its marked footprint in financial and motivating technical expertise. Potable water reuse and water banking on the Windhoek aquifer have technological in-roads that present enormous lessons apart from the systematic conjunctive use of surface and groundwater sources. Stakeholder involvement, including industries or those impacting and or impacted by water pollution or affected with water shortages, have blended very well. Wet industries during emergency drought periods adaptively abstract brackish groundwater and treat it on site using reverse osmosis technologies, which are some of the sustainable strategies to the city's water supply.

The water sector key stakeholders and experts in Namibia (inclusive of those in Windhoek –NamWater, MAWLR, Cabinet Committee on Water Security and the city, wet industries, Basin Management Committee, stakeholders and water users) have worked as a team and combined efforts in planning water resources supported by CA modelling. Daily monitoring and assessment of the water resources and water demands have assisted in presenting real time data and information as decision-making tools on the critical water supply situations. Private sector involvement in water sector planning and implementation as well as the existing public-private partnerships, has had remarkable success in Windhoek's water supply. The reclaimed water dual pipelines separating semi-purified water for irrigation and domestic use are bearing fruit.

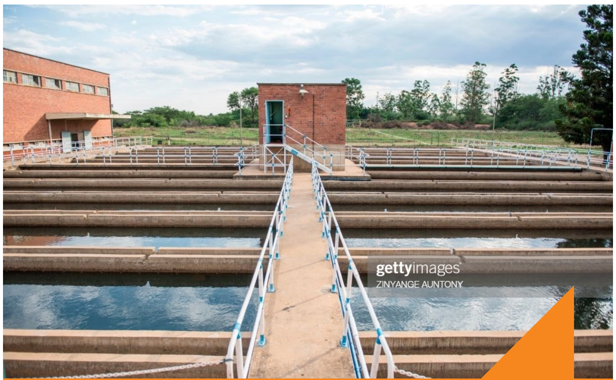
Resilience in the use of old infrastructure and controlling non-revenue water are factors contributing to sustainable water management in the face of climate change challenges. Water demand management through incentive and disincentive water tariffs and other water demand management strategies have reduced the city's per capita consumption to admirable ranges (140 to 160 L/cap.d ). On the long-term water supply forecast, Windhoek desperately requires to secure this either from the Okavango River, southern dams or desalinated water from the Atlantic Coast, whichever is cheaper and the preferred option. The major constraint with long-term water supply sources is that they are costly and require high capital funding. According to this case study's water demand projection for Windhoek, the water deficits will be in the order of 30 $Mm^3$ in 2050 and may increase to ±55 $Mm^3$ in 2080.

The lessons as presented in this case study should be shared with other countries facing similar challenges. The water sector in Namibia should secure an additional long-term water source otherwise the gains alluded to in this document might not continue.

The Green Climate Fund should be easily accessible and "friendly" to the vetted and highly vulnerable cities, like Windhoek, to climate change. The real and critical transformative climate projects require huge capital input and by their nature are less bankable. It is for this reason that many vulnerable cities have not implemented these sustainable solutions. Thus, to de-risk these projects, funding should be more accessible and allow for easy credit by ring-fencing the projects. Such special funding trial models to mitigate looming water supply crises should be tried with eligible cities like Windhoek, given that water supply infrastructure funding is not generic.

CHAPTER 6

# Water supply in Shanghai




A case study by
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## 6.1 INTRODUCTION AND BACKGROUND

Shanghai is the city with the largest urban population density in China, and the United Nations has designated it as one of the six major cities with shortage of drinking water in the 21st century. Moreover, coastal cities like Shanghai may have various potential risks caused by climate change and variability. This chapter deals with how Shanghai has dealt with water supply challenges that have been compounded by climate change and variability as well as rapid urbanization.

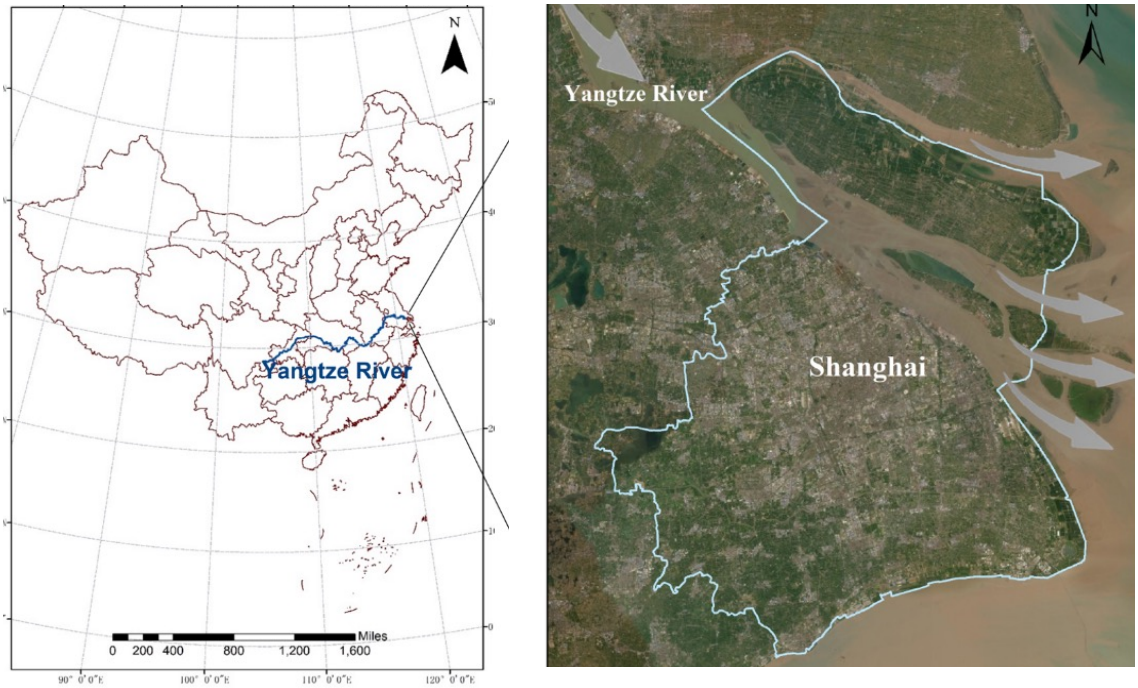
Shanghai has four major water reservoirs that are fed from the Yangtze and Huangpu river systems. Even though water resources in Shanghai seem to be sufficient, the city still faces acute challenges such as extreme cold waves or drought.

In terms of the city's current water consumption, the proportion for industrial use is relatively high, followed by that for residential. However, industrial water consumption is decreasing yearly due to deindustrialization and the strengthening of industrial water conservation practices. In order to entice residents to conserve water, Shanghai adopted a multitier water pricing system. In addition, Shanghai Waterworks are also gradually implementing advanced treatment technologies for all plants to improve water quality.

The purpose of this chapter is to provide reference for the management of water supply systems in other developing areas, such as African countries.

Shanghai is in east China, between 120°52 'and 122°12' east longitude and 30°40 'and 31°53' north latitude (see figure 6.1). Located at the mouth of the Yangtze River, Shanghai is served by the Yangtze and Huangpu Rivers, Suzhou Creek and some other tributaries. Among them, the average annual run-off of the main stream of the Huangpu River is 319 $m^3/s$, and the average annual flow

Figure 6.1: Map of Shanghai




Source: The satellite data are from https://map.tianditu.gov.cn/2020/

is 10 billion m$^3$. The annual water volume of Shanghai's water resources generally fluctuates in the range of 5–23 billion m$^3$.

In 1927, Shanghai municipality was formally established and divided into 20 suburban districts. Since China started its opening-up economic policy to the world in 1978, Shanghai has become the leader in drawing development to the Yangtze River Delta. It is in this context that Shanghai started its rapid urbanization process. Huge investments and foreigners flooded Shanghai, contributing to its prosperity and development. The city has since become China's most developed and a centre for international economic and financial trading, shipping, and technological innovation. In the next five years, Shanghai will become a modern international metropolis with significant global influence.

Shanghai occupies 6,340.50 km$^2$, a relatively small total area, which ranks it 29$^{th}$ based on area coverage among China's 34 provincial capitals and municipal cities. The seventh national census showed that the permanent population of Shanghai on 1 November 2020 was 24.87 million, confirming its status as the most populous city in China (see figure 6.2). Of this population, people from the Yangtze River Delta account for the majority of migrants to the city, which includes foreigners. Most migraants came to Shanghai in the 1980s and 1990s and gradually became local residents. In Shanghai, the proportion of permanent residents from other provinces and cities is 42.1 per cent. Therefore, the most significant factor driving the city's population growth is the inflow from other provinces and cities. Shanghai's population growth pattern is similar to other cities in the Yangtze and Pearl River deltas and the Chengdu Chongqing urban agglomeration. Shanghai's gross domestic product and per capita have grown rapidly since 1978. From 2010 to 2019, GDP in Shanghai grew by 113 per cent, and per capita GDP grew by 94 per cent (see figure 6.3).[0]

Figure 6.2: Population in Shanghai 1978–2020

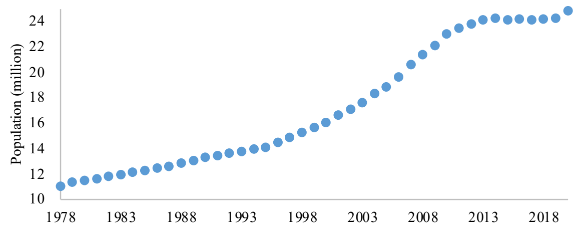
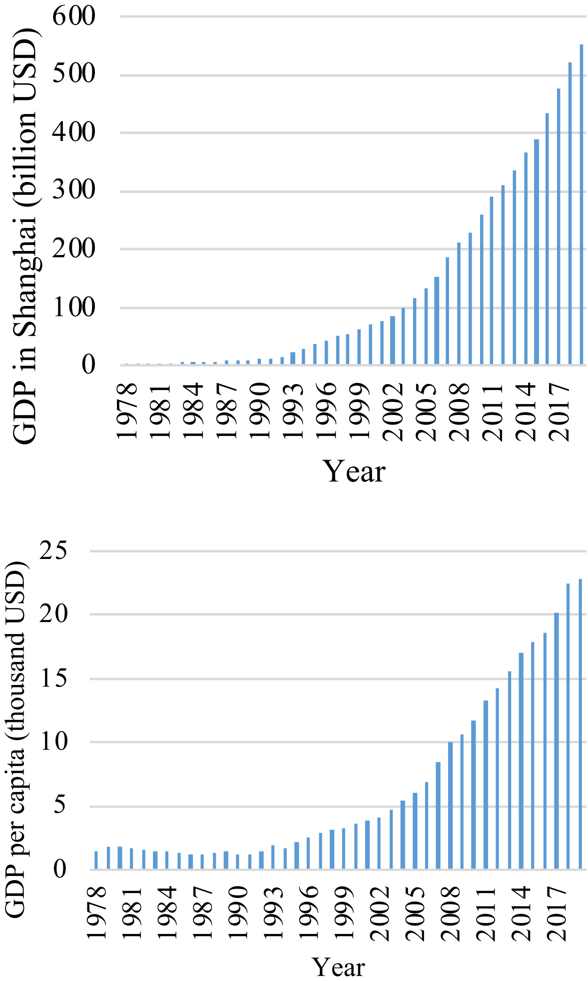


Figure 6.3: GDP (left), GDP per capita (right) in Shanghai 1978–2019




## 6.2 CLIMATE CHANGE AND WATER AVAILABILITY

Climate change has an impact on water sources and urban water supply. An accurate understanding of the local climate change in Shanghai will be of great help to the water supply system.

The 100-year average temperature of Shanghai urban area is 16°C, and the difference between the hottest and coldest years is 4.0°C. From 1873 to 2020, the annual average temperature, annual average maximum temperature and annual average minimum temperature of Zikawei in Shanghai were 16.0°C, 20.6°C and 12.5°C, respectively. The temperature in Shanghai has increased significantly in the past 100 years, with the fastest warming from 1980 to 2009, reaching 0.96°C/decade, and the nighttime warming was greater than the daytime warming. There has been a significant increase in temperature from 1873 to 2020 (see figure 6.4), and the average temperature warming rate was 0.18°C/decade. The period from 1980 to 2009 had the fastest warming rate in the past 100 years, in which the average temperature increase rate was 0.96°C/decade.

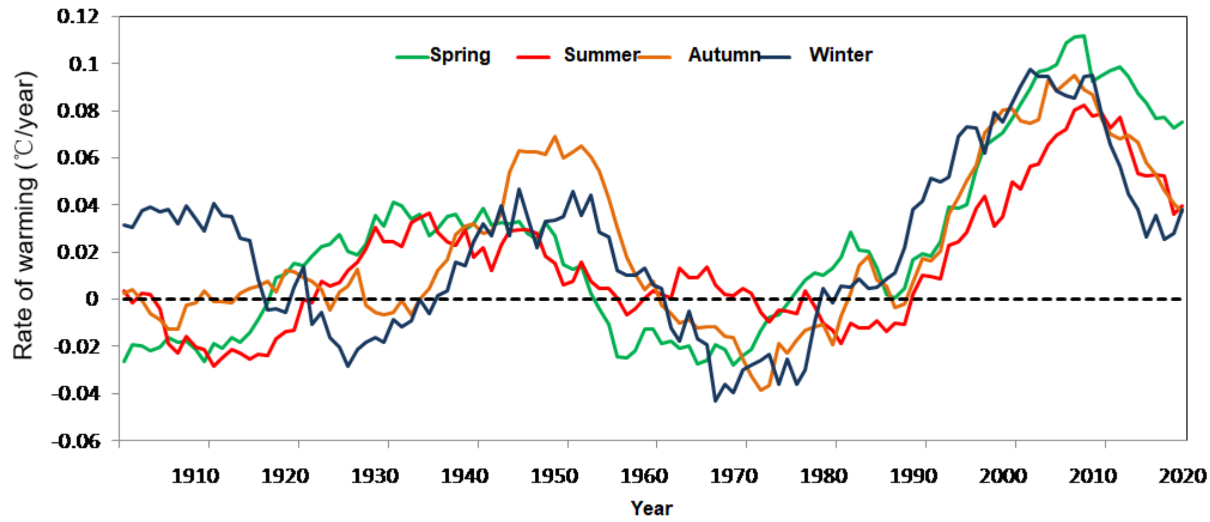
The 100-year warming rate of the autumn season was the largest and the fastest warming rate alternates between seasons, with the fastest warming occurring in spring since 1975, including 1.12°C/decade from 1980 to 2009. From 1873 to 2020, Shanghai experienced its fastest warming period in autumn (0.20°C/decade), almost equal warming in spring (0.19°C/decade) and winter (0.18°C/decade), and summer (0.13°C/decade) had the lowest warming rate. The seasonal warming rate varies significantly among every decade, and the fastest warming seasons alternate. Since 1975, spring warming has accelerated to become the fastest warming season of the four seasons, amongst which the spring warming rate reached the maximum seasonal warming rate of 1.12°C/decade from 1980 to 2009. Since 2010, the warming of the four seasons tended to slow down, but spring is still the fastest warming season.

From 1873 to 2020, the number of annual average hot days,[9] high-temperature strength[10] and longest consecutive high-temperature days[11] were 14ºC, 36.3ºC and 6ºC, respectively. There were 55 high temperature days in 1934, which was the highest number ever, and there were no high temperature days in 1877 and 1882 (see figure 6.5). In the summer of 2017, the highest temperature in Xujiahui was 40.9º, and there were 11 consecutive days above 37ºC, which were the highest for the same period since the establishment of meteorological records in 1873.

From 1874 to 2020, the average annual precipitation in central Shanghai was 1,187 mm/year, with high inter-annual variability, and the difference between the maximum yearly total precipitation and minimum one was 1,084.5 mm. The precipitation amount and intensity have increased significantly in the past century. The precipitation amount increased by 13.8 mm/decade. Although precipitation increased in all seasons, it was the fastest in the summer and flood seasons.[12]

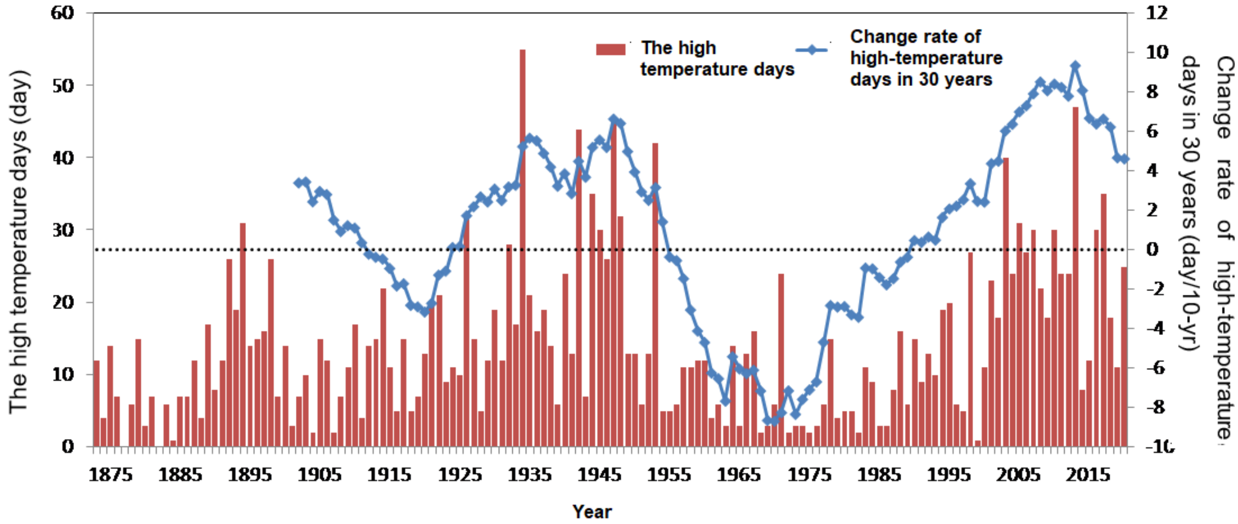
From 2016 to 2020, the area of Shanghai covered by lakes has grown. Shanghai total area covered by rivers and lakes has increased from 616.5 km$^2$ in 2016 to 649.2 km$^2$ in 2021. The water surface ratio of rivers and

Figure 6.4: The 30-year change in rate of average temperature in Xujiahui, Shanghai 1873–2020




Note: The 30-year change rate in 2020 refers to the change rate from 1991 to 2020, and so on.

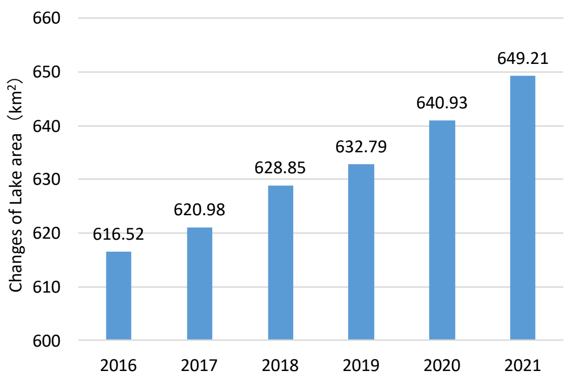
Figure 6.5: Changes of annual average high temperature days and 30-year change rate at Xujiahui Station in Shanghai 1873–2020




Note: The 30-year change rate in 2020 refers to the warming rate from 1991 to 2020, and so on.

lakes increased from 9.7 per cent to 10.2 per cent. This increase is mainly because, in recent years, the State and people have been paying greater attention to some environmental functions, such as water storage and drainage of lakes, and the Government and enterprises have taken concrete steps to achieve planned objectives (see figure 6.6). At the same time, the steady economic growth has also created conditions to meet the ecological and environmental needs of residents. According to a study on flooding scenario simulation of future extreme precipitation in Shanghai, the results predicted that precipitation in Shanghai before the 2050s will show a trend of increasing and decreasing alternations, followed by a decreasing trend, and then a marked decrease around the 2070s. Regarding spatial distribution, predictions are that the duration of waterlogging to the

Figure 6.6: Changes of lake area in Shanghai in recent years




Source:
Shanghai River and Lake Report. Available at http://swj.sh.gov.cn/hhbg/index.html

east and south of the Huangpu River will be shorter than that of the west and north. When using high flood return periods, the depth of waterlogging is predicted to increase and this will affect the safety and stability of water sources to a certain extent.

Section 6.4.1 of this chapter will specifically describe the impact on water sources in Shanghai under extreme and non extreme climate change scenarios.

## 6.3 WATER QUALITY STANDARDS FOR SURFACE WATER AND WATER SUPPLY IN CHINA

All drinking water supply sources in China shall comply with the national Environmental Quality Standard for Surface Water ( code GB3838-2002) and the Standard for Groundwater Quality (code GB/T14848-2017) (see table 6.1 and appendix). The water supply quality shall comply with the national hygienic [standard for drinking water (GB5749-2022). At the same time, the Shanghai local drinking water quality standard (DB31/T1091-2018) shall be implemented (see appendix).

Government companies and water bureaus must implement relevant standards. To better meet the above standards, Shanghai's water industry has strengthened its water quality detection capacity and implemented various quality assurance measures. For example, public water supply enterprises should measure 49 indicators at least once a month and 111 indicators at least once every half year. During the peak water supply periods in summer, the measurement of ordorous substances 2-methylisoborneol and geosmin should be increased. All reservoirs should strengthen monitoring and pay attention to the changes in algae. Then they should add sodium hypochlorite and other chemicals, when necessary, to water sources in portions compliant with the technical regulations for dosing emergency chemicals. In addition, the performance of advanced treatment processes of water treatment plants should be further improved.

Shanghai Municipality's regulations stipulate punishments for management units of secondary water supply facilities that fail to provide safe drinking water to domestic users. Where service results in poor water quality, the municipality's Health and Family Planning Department fines the unit the local equivalent of USD 157–1,571. In serious cases, a unit would be fined USD 1,571–4,713. However, the most important need is to determine the causes of poor water quality and solve them in a timely manner. If the toxic and harmful indicators exceed the standard permissible limit, then production must stop (see table 6.1). All waterworks have water quality emergency plans.

Table 6.1: Standard limits of chemicals in surface water due for potable water plants

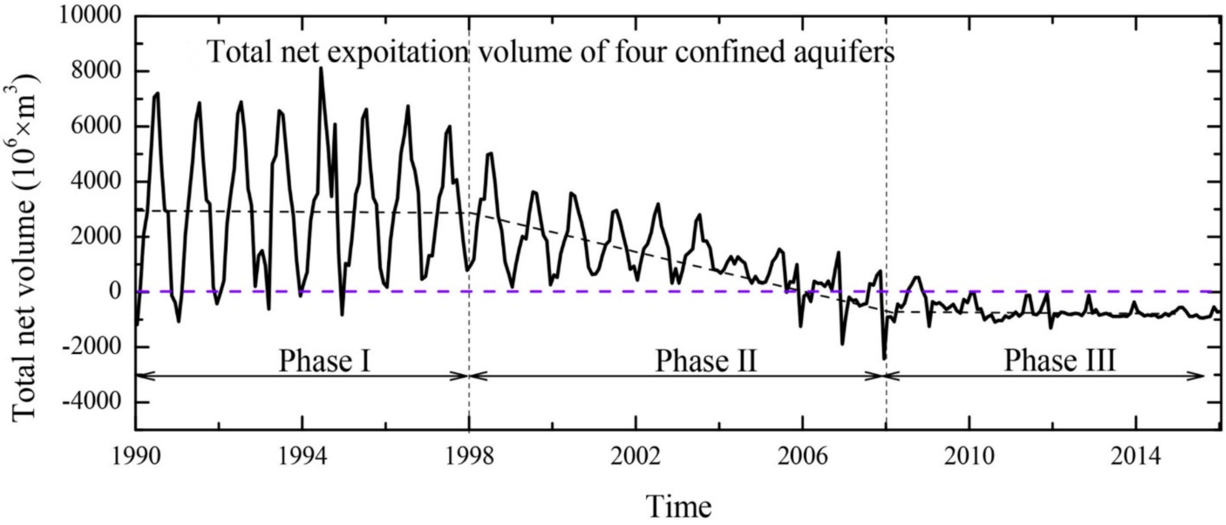
| No. | Event | Standard value |
|---|---|---|
| 1 | Sulfate (calculated by $SO_4^{2-}$) | 250 |
| 2 | Chloride (calculated by $Cl^-$) | 250 |
| 3 | Nitrate (calculated by N) | 10 |
| 4 | Fe | 0.3 |
| 5 | Mn | 0.1 |

**Table 6.2: Routine water quality indicators and limits in drinking water for Shanghai[0]**

| Parameter | Limit value |
|---|---|
| 1. Microbial index | |
| Total Coliform (MPN/ 100 mL or CFU/100 mL) | Not Detected |
| Thermotoletant coliform bacteria (MPN/ 100 mL or CFU/100 mL) | Not Detected |
| Escherichia coli (MPN/ 100 mL or CFU/100 mL) | Not Detected |
| Aerobic bacterial count (CFU/mL) | ≤50 |
| 2. Toxicological indicators | |
| As (mg/L) | ≤0. 01 |
| Cd (mg/L) | ≤0. 003 |
| Cr (hexavalent) (mg/L) | ≤0. 05 |
| Pb (mg/L) | ≤0. 01 |
| Hg (mg/L) | ≤0. 0001 |
| Se (mg/L) | ≤0. 01 |
| Sb (mg/L) | ≤0. 005 |
| Cyanide (mg/L) | ≤0.05 |
| Fluoride (mg/L) | ≤1.0 |
| Azotate (Calculated as N element) (mg/L) | ≤10 |
| Nitrite-nitrogen (mg/L) | ≤0.15 |
| Trichloromethane (mg/L) | ≤0.06 |
| Bromoform (mg/L) | ≤0.1 |
| Trihalomethane (mg/L) | Sum of the ratios of measured concentrations to limits for various compounds ≤0.5 |
| Carbon tetrachloride (mg/L) | ≤0.002 |
| Bromate (when using ozone) (mg/L) | ≤0.005 |
| Formaldehyde (when using ozone) (mg/L) | ≤0.45 |
| Chlorite (when disinfecting with chlorine dioxide) (mg/L) | ≤0.7 |
| Chlorade (when disinfecting with combined chlorine dioxide) (mg/L) | ≤0.7 |
| 3. Sensory traits and general chemical indicators | |
| Chroma (platinum cobalt colour unit) | ≤10 |

| Parameter | Limit value |
|---|---|
| Turbidity (NTU) | ≤0.5 |
| Odour and taste | No odour |
| Visible to the naked eye | Not Detected |
| pH | 6.5≤pH≤8.5 |
| Al (mg/L) | ≤0.2 |
| Fe (mg/L) | ≤0.2 |
| Mn (mg/L) | ≤0.05 |
| Cu (mg/L) | ≤1.0 |
| Zn (mg/L) | ≤1.0 |
| Chloride (mg/L) | ≤250 |
| Sulfate (mg/L) | ≤250 |
| Total dissolved solids (mg/L) | ≤500 |
| Total hardness (mg/L) | ≤250 |
| Oxygen consumption (mg/L) | ≤2 Water source limitation: 3 when the oxygen consumption of raw water is more than 4 mg/L |
| Volatile phenols (Calculated as phenol) (mg/L) | ≤0.002 |
| Anionic synthetic detergent (mg/L) | ≤0.2 |
| Ammonia nitrogen (Calculated as N element) (mg/L) | ≤0.5 |
| 4. Radioactivity index | |
| Total alpha activity (Bq/L) | ≤0.5 |
| Total beta activity (Bq/L) | ≤1 |
| 5. Disinfectant index | |
| Free chlorine | Contact time with water≥30 min0.5 mg/L ≤Factory water allowance≤ 2mg/LWater allowance at the end of pipe network≤0.05 mg/L |
| Total chlorine | Contact time with water≥120 min0.5 mg/L ≤Factory water allowance≤2 mg/LWater allowance at the end of pipe network≤0.05 mg/L |
| Ozone | Contact time with water≥12 minFactory water allowance≤0.3 mg/LWater allowance at the end of pipe network≤0.02 mg/Lif chlorine injectiontotal chlorine≥0.05 |
| Chlorine dioxide | Contact time with water≥30min0.1 mg/L≤ Factory water allowance≤0.8 mg/LWater allowance at the end of pipe network≤0.02 mg/L |

Figure 6.7: The total net volume of four confined aquifers over time




## 6.4 WATER SOURCES AND SUPPLY IN SHANGHAI

### 6.4.1 Water sources in Shanghai

Shanghai has two major sources of water, the Yangtze and Huangpu Rivers, as well as a network of scattered water bodies. Due to rapid economic development, the problem of water pollution has become urgent, although Shanghai is relatively rich in water resources. At national level, however, Shanghai is regarded as a water-shortage city. At a global level, the United Nations also classifies Shanghai as one of the six major cities that have insufficient drinking water in the 21st century.

Groundwater was once the main source of public water supply in some areas of Shanghai because of its good quality and relatively simple treatment requirements. Since the 1960s, Shanghai's industrial production has increased significantly. Due to the shortage of tap water, the number of new deep wells has increased every year, resulting in a sharp increase in groundwater exploitation and depletion (see table 6.7). In the 1960s and 1970s, the annual groundwater exploitation was more than 150 million $m^3$. Due to the growth rate of urban construction and the massive exploitation of groundwater, the problem of land subsidence is prominent, which has attracted much attention from the municipal government. The government has adopted a series of measures to solve the problem, such as strictly controlling the number of new deep wells, increasing groundwater recharge, and changing the main water source from groundwater to surface water. Typically there are three types of deep well in Shanghai: (1) specialized recharge well, which is only for recharge; (2) supply and recharge well, which is for water exploitation and recharge;  (3) emergency supply and recgarge well, which is only used in case of emergency for water exploitation and recharge. By around 2000, the above measures had achieved results. The city's annual new shaft sinking was limited to less than 20, the annual groundwater abstraction volume was controlled from the historical peak of 200 million $m^3$ to less than 100 million, and the recharge volume remained at around 15 million $m^3$. The rebound of groundwater level is now evident, and the average annual land settlement is controlled at about 10 mm, which curbs the continuous land settlement.[0] In 2020, the annual water abstraction from surface water sources was 7.247 billion $m^3$, that of groundwater 1 million $m^3$, and other water sources 14 million $m^3$. However, the exploitation volume of deep groundwater in Shanghai is planned to be controlled within 5 million $m^3$. The artificial groundwater recharge needed is 18.1 million $m^3$ to keep the artificial recharge amount greater than that extracted. Figure 6.7 shows the total net exploitation volume of the four aquifers over time. It can be seen that groundwater exploitation has been decreased sharply in phase II. In phase III, the net exploitation volume is stable and the extracted volumes can be almost neglected.

In an extreme scenario, with climate change and urban development, the extreme precipitation and increasing waterlogging depth in the future are expected to affect the water supply safety and stability of the Huangpu River water source to a certain extent. For instance, in the Yangtze River Estuary, due to climate change and rising sea levels, salt tides and other phenomena have affected the raw water supply. Sea level rise is a major concern for coastal settlements. The Huangpu River basin is a typical, vulnerable area of storm floods. Some scholars have predicted that the relative sea level rise in 2030 and 2050 will be 170 mm and 390 mm, respectively, from the three aspects of absolute sea level rise, tectonic and compaction settlement. Based on the high-precision flood numerical model, two extreme storm flood scenarios in 2030 and 2050 are simulated. The results show that both banks of the Huangpu River may be submerged, and this phenomenon the upstream area will be more serious than that at the middle and lower reaches.[0]

In non-extreme cases, Shanghai currently abstracts water from the Yangtze River system and the volume of raw water from the mainstream of Yangtze (1,162 billion $m^3$ in 2020) is much greater than the water intake (76.62 billion $m^3$ in 2020), resulting in less fluctuation to the water volume of the river. Climate change-induced high temperatures and dry days may reduce the water volume of some lakes in the upper reaches but have less impact on Shanghai. Furthermore, one of the operational risks of the Shanghai water supply system may also come from unusally cold weather. The minimum temperature of the whole urban supply system was originally designed to be -7°C, if the temperature is lower than -10°C due to a cold wave, the secondary water supply facilities (that is, exposed small pipelines) will be frozen, affecting the domestic water supply, and the large pipelines will burst. More importantly, there is the need to consider all potential natural disasters and human impacts in the upper and middle reaches of the Yangtze River and make corresponding emergency plans.

The available water supply in the upper reaches of the Huangpu River is limited, and the water quality is affected by upstream and riparian pollution. Some scientists analysed the water quality data of Shanghai from 1979 to 2016 and found that heavy metal, organic contamination, and microbes polluted the raw water sources of the Huangpu River and Yangtze River Estuary. They noticed that the average concentrations of these contaminants in the Huangpu were almost double that of the Yangtze River Estuary.[0] Moreover, some water sources do not meet the raw water quality standards. Therefore, some reservoirs need to be built to ensure that the supply of raw water will not be affected.

### 6.4.2 Water supply in Shanghai

According to the recent Shanghai water supply master plan, Shanghai will build an urban water supply system with "water-saving priority, safety and high quality, smart low-carbon and efficient service" by 2035. Moreover, the water quality will be at par with that of developed countries. Based on planning requirements, the maximum daily water demand in the long term is will be controlled at 13–14 million $m^3$/day. In 2020, the total amount of water used in Shanghai was 7.262 billion $m^3$.

Figure 6.8 on water use categories in the city shows that agriculture accounted for 1.522 billion $m^3$, industry 3.301 billion $m^3$ (including 2.468 billion $m^3$ for thermal power industry), public urban 966 million $m^3$, residential domestic 1.389 billion $m^3$, and ecological environment consumption 84 million m.[3] According to Shanghai statistics yearbook, the daily domestic water

Figure 6.8: Water consumption type and quantity in 2020

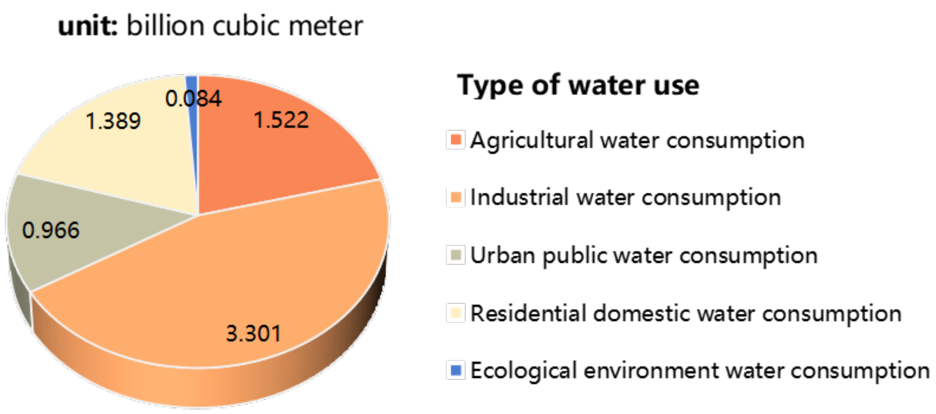
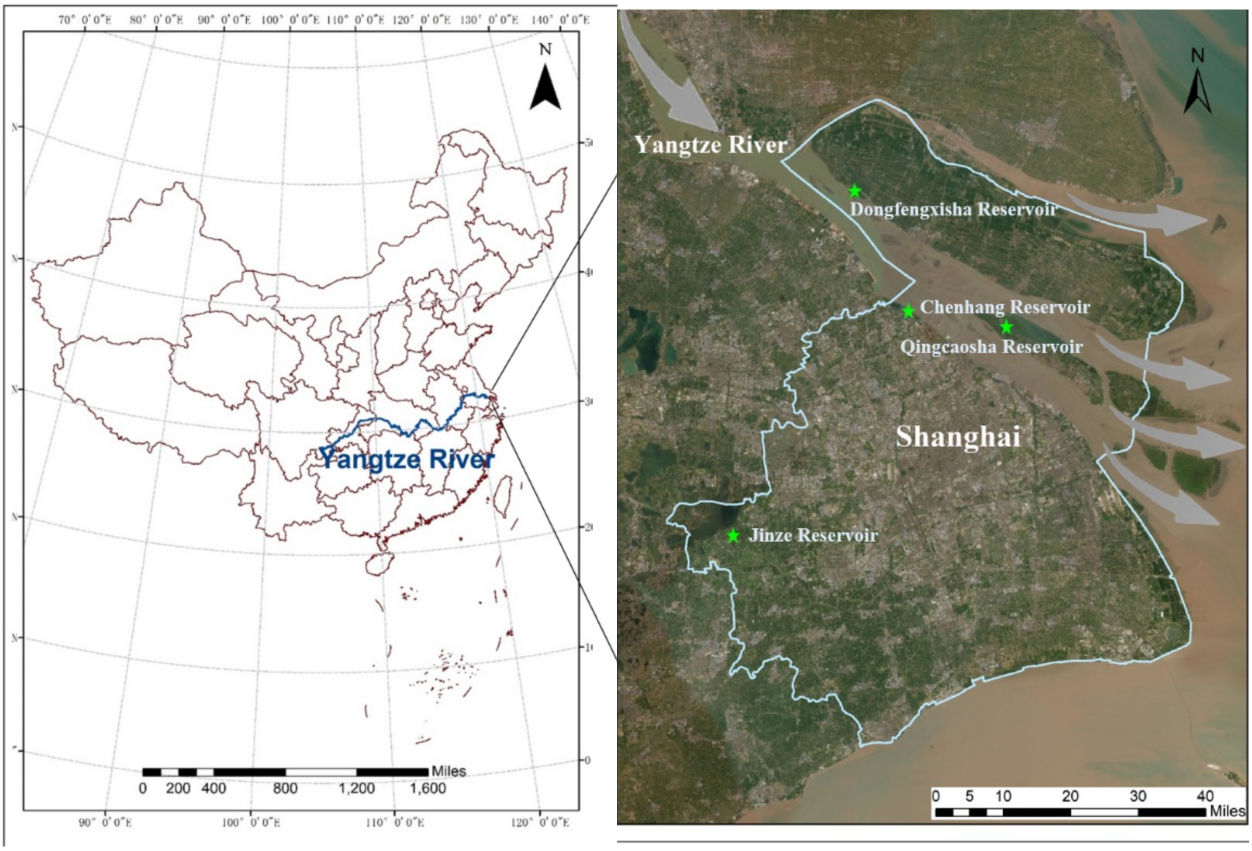


Figure 6.9: Location and scope of four major drinking water source protection areas in Shanghai




consumption per capita has been relatively stable in the past 10 years at about 120 litres per capita per day. However, the comprehensive water consumption per capita shows an obvious downward trend, from 311 litres per capita per day in 2008 to 259 litres per capita per day in 2020. This downward trend is mainly due to the adjustment of economic structure and the decline of industrial water consumption, the reuse rate of industrial water above designated size was 93.55 per cent in 2020, and the possibility that Shanghai's industrial water consumption may be further reduced because of the gradual implementation of deindustrialization and industrial water conservation. Shanghai is one of the first batch of water-saving cities in China. Shanghai has taken several measures to manage the use of water: these measures include the building of water-saving units at the municipal and district levels, updating the standards of water-saving evaluation, and stopping projects that failed to review the water-saving evaluation. Other measures include strengthening the management of water quota and planned water use, a pilot demonstration project of sewage resource utilization appropriate for local conditions. After more than 20 years of continuous efforts, the construction of water-saving cities has achieved remarkable results. In 2020, Shanghai saved 6 million m$^3$ of water, with a maximum daily water saving of 21,400 m.[30]

The water management system of Shanghai consists of f government departments and companies they authorizes. The municipal government is responsible for stipulating the water tariff. Before tariff adjustment, the municipal government seeks public opinion on the proposed tariff increase. The advantage of this is that it can keep the water supply tariff stable for a long time and less affected by other external factors. The relevant operation, management and infrastructure costs are met by municipal government grants and financial subsidies. The franchised water supply enterprises meet their operational costs and get their profits from water sales. They can also get some municipal government subsidies for the construction of advanced treatment

### Table 6.3: Basic attributes of water sources in Shanghai

| Name of water source | Coverage km$^2$ | Storage capacity $10^6$ m$^3$ | Retention time d | Water depth m | Serviced population $10^6$ |
|---|---|---|---|---|---|
| Qingcaosha Reservoir | 66.15 | 43.5 | ~20 | 0~17 | ~13 |
| Chenhang Reservoir | 1.35 | 8.3 | 3~5 | 5~6 | ~3.5 |
| Jinze Reservoir | 2.7 | 8.17 | 3~5 | 4~7 | ~6.5 |
| Dongfeng Xisha Reservoir | 3.74 | 8.9 | 4~7 | 0.2~5 | ~0.7 |

### Table 6.4: Tap water data in Shanghai

| Index | 2010 | 2015 | 2018 | 2019 |
|---|---|---|---|---|
| Number of water treatment plants | 105 | 37 | 37 | 37 |
| Water supply capacity (×$10^6$ m$^3$/day) | 11.31 | 11.37 | 12.5 | 12.5 |
| Length of water supply pipeline (km) | 31 182 | 36 383 | 38 414 | 38 869 |
| Total water supply (×$10^6$ m$^3$) | 3 090 | 3 122 | 3 055 | 2 979 |
| Total water sales (×$10^6$ m$^3$) | 2 444 | 2 458 | 2 435 | 2 399 |
| Industrial water (×$10^6$ m$^3$) | 580 | 494 | 433 | 404 |
| Non-industrial water (×$10^6$ m$^3$) | 602 | 711 | 766 | 773 |
| Residents' domestic water (×$10^6$ m$^3$) | 980 | 988 | 1 059 | 1 089 |
| Other (×$10^6$ m$^3$) | 282 | 265 | 177 | 133 |
| Daily domestic water consumption per capita (Litre) | 117 | 112 | 120 | 123 |

Source: Shanghai Bureau of Statistics, available at http://tjj.sh.gov.cn/tjnj/nj20.htm?d1=2020tjnj/C1109.htm

### Table 6.5: Basic information on tap water in Shanghai from 2019 to 2021

| Indicators | 2019 | 2020 | 2021 |
|---|---|---|---|
| Number of water plants | 37 | 38 | 38 |
| Water supply capacity ($10^4$ m$^3$/day) | 1 250 | 1 221 | 1 221 |
| Length of water supply pipe (Km) | 38 869 | 39 552.5 | 39 690 |
| Total amount of water supplied (100 billion m$^3$) | 29.79 | 28.86 | 30.08 |
| Total amount of water sold (100 billion m$^3$) | 23.99 | 23.59 | 24.77 |
| Industrial water use | 4.04 | 3.89 | 4.05 |
| Non-industrial water use | 7.73 | 6.95 | 7.89 |
| Residential water use | 10.89 | 11.37 | 11.57 |
| Other Water use | 1.33 | 1.14 | 1.26 |

systems, which will, in turn, reduce their operational costs and increase their profits. Although most water supply departments in Shanghai are running at a loss, municipal government subsidies are gradually increasing, and the cost of water is also rising reasonably to ensure financial sustainability as much as possible.

In order to meet rising demand, Shanghai has adopted a raw water supply approach of "simultaneous development of two rivers, centralized water intake, reservoir water supply and one network dispatch". Therefore, Shanghai has built four reservoirs for water supply: the Qingcaosha Reservoir in the north-west of Changxing Island; the Chenhang Reservoir outside the Yangtze River embankment in the east of Luojing Town, Baoshan District; the Jinze Reservoir  on the north nank of the Taipu River in the west of Jinze Town; the Dongfeng Xisha Reservoir in the north of the upper area of the south branch of the Yangtze River Estuary and the south-west of Chongming Island (see figure 6.9). During the 2017–2019 period, the Qingcaosha Reservoir supplied 54.1 per cent  of the required water, the Jinze Reservoir 24.5 per cent, the Chenhang Reservoir 19.3 per cent and the Dongfengxisha Reservoir 2.1 per cent. (see table 6.3).[0]

The water supply system guarantees  Shanghai as it strives to achieve rapid development and maintain a high-quality standard of life. It is also the base supporting the development of a modern international metropolis with leading global influence. According to the infrastructure service requirements to sustain 30 million people in the Shanghai urban master plan (2017–2035), and in alignment with the coordinated development of various regions, Shanghai is planning to establish and promote the overall water supply layout of "1 network, 2 areas and 39 plants". The "1 network" refers to a single water supply network for the whole city; "2 areas" refers to the main urban water supply area and the suburban water supply area; "39 plants" refers to the 39 central water treatment plants integrating urban and rural areas. At the same time, the rapid expansion of Shanghai's infrastructure has also provided a strong impetus to the realization of the city's urban master plan. These measures are mainly to improve the water supply capacity of Shanghai and ensure water quality according to local standards. With the continuous development of the economy and the sustained increase of population, the capacity of Shanghai water supply is also facing a huge test. In the past three decades, Shanghai has adopted a variety of engineering measures according to the actual situation, continuously improved the raw water supply network, and gradually built a water supply source security system. From this, it has achieved good raw water quality, met the water supply demand volume and ensured water supply security. The water supply data for Shanghai in selected years is shown in tables 6.4 and 6.5.

Figure 6.10: Aerial view of Yangshupu Waterworks

Figure 6.11: Ten conventional treatment processes of Yangshupu Waterworks

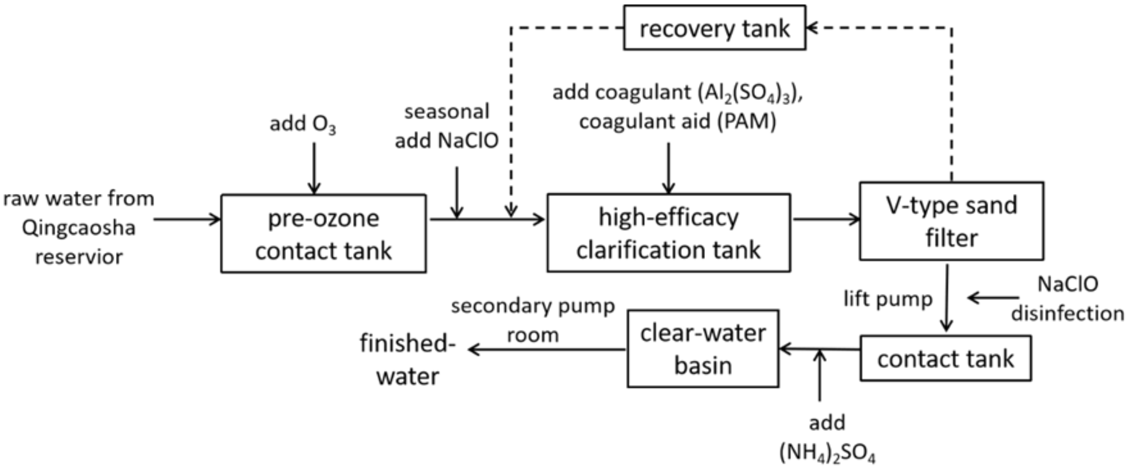
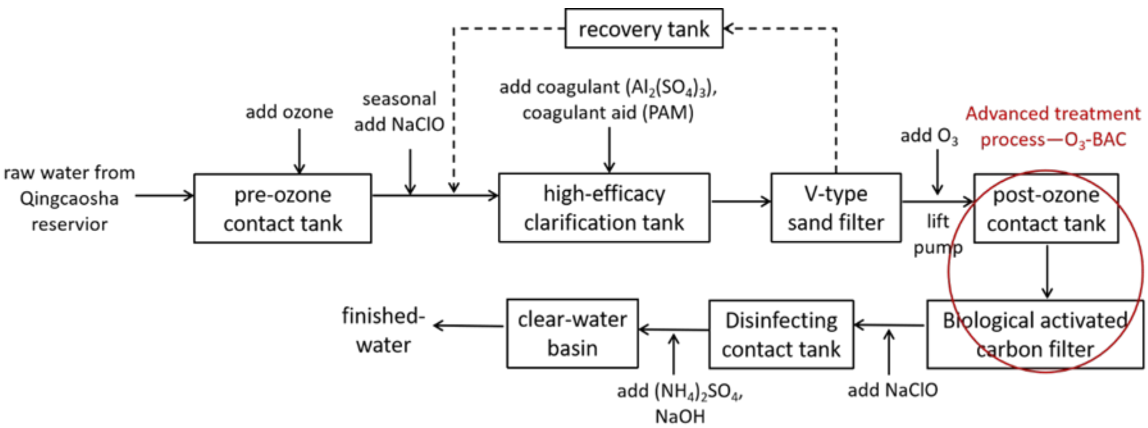



Figure 6.12: Conventional and advanced treatment process of Yangshupu Waterworks




## 6.5 TREATMENT PROCESS OF SHANGHAI WATERWORKS

Shanghai has adopted, for the most part, advanced water treatment processes to deal with emerging or non-traditional pollutants,. By the end of 2020, the coverage rate with this treatment process of Shanghai waterworks had reached 60 per cent. During the "14th Five-Year Plan" period, Shanghai aims to install advanced treatment processes at all its waterworks abstracting raw water from the Yangtze River. This way, these facilities will ensure a higher-level quality of tap water to residents. Shanghai Waterworks' advanced treatment technology is based on an ozonization and biological activated carbon adsorption ($O_3$-BAC) process.

### 6.5.1 Yangshupu Waterworks

Treatment scale: The water supply capacity of the waterworks has reached 1.48 million $m^3$/d, and the annual water supply exceeds 400 million $m^3$, which provides industrial and domestic water to about 3 million citizens. Yangshupu Waterworks has five water production lines. One of these was upgraded and transformed into an advanced treatment line in 2009, as shown in figure 6.10 . In May 2020, this waterworks with a design capacity of 1.2 million m3/d started the advanced treatment project in a comprehensive manner. The facility is due to start operations in 2024. After the renovation, all production lines in the plant will adopt the advanced treatment process of ozonization and biological activated carbon. Figures 6.11 and 6.12 show the current and envisaged flow charts for the Yangshupu Waterworks.

Figure 6.13: Water purification process of Dachang Waterworks

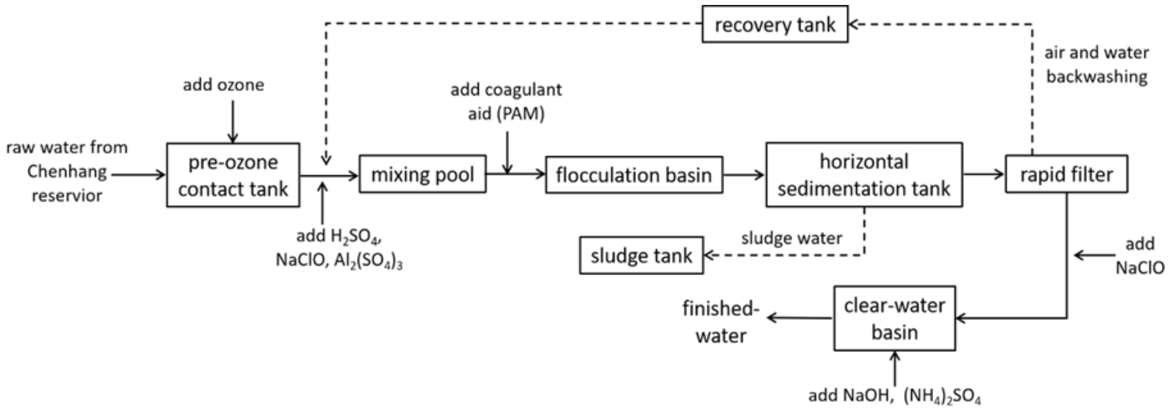
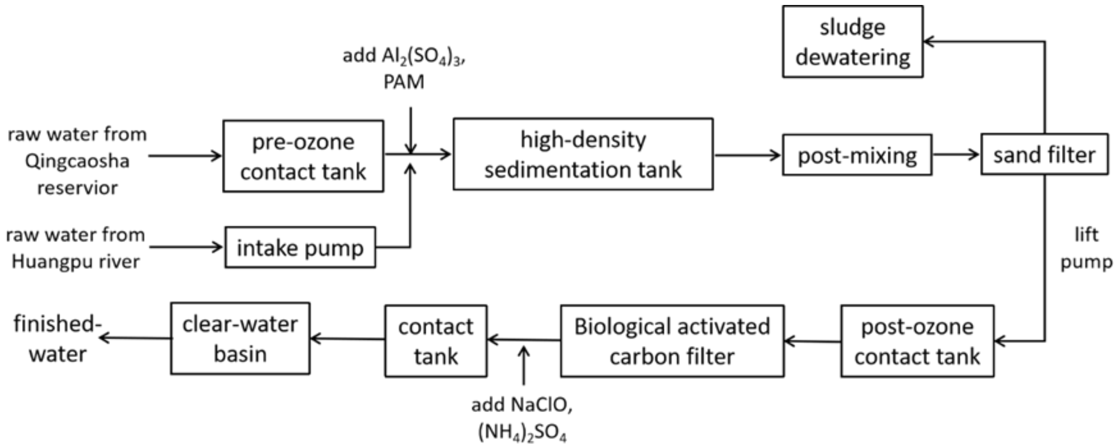



Figure 6.14: The whole production process of Nanshi Waterworks




### 6.5.2 Dachang Waterworks

Treatment scale: The design capacity is 400,000 m$^3$/d

Process flow chart (see figure 6.13): According to the treatment requirements and water quality conditions of raw water from the Chenhang Reservoir, Dachang Waterworks adopted the conventional treatment processes. After pre-oxidation, aluminum sulfate and flocculation of polyacrylamide (or PAM) are used as coagulant and coagulant aid, respectively. This treatment separates the precipitate in the horizontal sedimentation tank. Then, air-water backwashing rapid filter is applied to separate the solution further. The last stage is disinfection and clear-water basin, in which sodium hypochlorite and ammonium sulphate are used to enhance the disinfection process.

### 6.5.3 Nanshi Waterworks

Treatment scale: the water supply capacity reaches 700,000 m$^3$/d

Process flow chart (see figure 6.14): The high-density sedimentation tank used in Shanghai Waterworks occupies a small area, high removal efficiency of suspended particles, short-running time and low turbidity. The water purification process of Shanghai Waterworks can deal well with the raw water quality with frequent algae in summer and meet the requirements of organic matter, chromaticity, turbidity and other parameters. In addition, the widely used ozonization-activated carbon advanced treatment process can remove odours and further improve the safety of water supply in Shanghai waterworks. For example, the presence of dimethyl isoborneol (2-MIB) in Qingcaosha Reservoir during summer exceeds safe limits significantly, which is the main cause of the odours. Subsequently, ozone was used in combination with biological activated carbon as an advanced oxidant, which significantly improved the removal rate of 2-MIB. Thus the process adopted in Shanghai Waterworks is an effective treatment process for microorganic polluted raw water. Moreover, in the treatment, poly aluminum chloride (PAC) is widely used as coagulants during all seasons, while some plants use aluminium sulphate. PAC accounts for 95 per cent of market share of products used to treat water for Chaina's drinking plants. Poly ferric sulfate and PAC are both used in the treatment of wastewater. From 8 million to 9 million tons of aluminum coagulants and ferric salts are used annually. PAC and polymerized ferrous sulphate (SPFS) for treatment of drinking water should comply with the national standard (GB 15892-2020)[27] and (GB/T 14591-2016)[0], respectively (see appendix).

### 6.5.4 Experiences of water supply in Shanghai

Shanghai is at the lowest reach of the Yangtze River; therefore it receives pollution from upstream areas. In addition, Shanghai forms part of a network of a river plain running through flat topography. This physical feature means the water flow velocity is relatively sluggish, and the retention time is quite long.

1. The first experience is that the Shanghai government has invested a great deal of money in environmental protection, wastewater treatment, drinking water purification and pipeline renovation. The constant upgrading of urban water infrastructure improves the city's water quality and safeguards public health.

2. The second experience is the adoption of multi-tier water pricing system, which is effective in contributing to water conservation (see table 6.6). Water fees rise progressively as water consumption increases. If people use more water, they have to pay higher tariffs. For example, a household consuming 220 $m^3$ of water or less a year pays USD 0.65 per cubic metre, which includes USD 0.36 for water supply and USD 0.32 for sewage treatment. Households whose annual water consumption is between 220 and 300 $m^3$ pay USD 0.90 per cubic metre, while those consuming more than 300 $m^3$ a year pay USD 1.36 per cubic metre. The monthly water fee is around USD 9.63 per household, accounting for 0.42 per cent of the average disposable income. This measure has been effective in encouraging Shanghai households to save water.

3. The third experience is the ecological protection of water sources. Feasible measures must be taken to ensure the reliable provision of water quality. Shanghai has implemented the "river chief system" that assigns municipal government officials to protect waterways in their area.Shanghai has implemented the "river chief system" that assigns municipal government officials are assigned to take charge of protecting waterways in their area. This "river chief system" is widely adopted in China to prevent pollution. Because the river chiefs are usually local officials, they provide effective water management.

## 6.6 CONCLUSIONS AND RECOMMENDATIONS

Going by Shanghai's water supply plan, the city will, in the next 15 years, move towards forming its "1, 2, 4, X" water source and raw water system layout. The "1" refers to a raw water connecting pipe network in the whole city, which interconnects the raw water systems in Qingcaosha and Chenhang on the Yangtze River and the upper reaches of Huangpu River, to promote mutual reinforcement and complementarity in water supply. The "2" means that the Yangtze and Huangpu Rivers should be developed simultaneously, and the connection with water resources in the basin should be strengthened. The "4" refers to four reservoirs; namely Jinze, the water source of the upper Huangpu River; Qingcaosha, Chenhang and Dongfeng Xisha, the water

**Table 6.6: Multi-tier pricing system of domestic water in Shanghai**

| | Household water consumption ($m^3$/Year) | Tap water price (\$/$m^3$) | Drainage fee (\$/$m^3$) | Total water price (\$/$m^3$) |
|---|---|---|---|---|
| 1st tier | 0–220 | 0.36 | 0.32 | 0.65 |
| 2nd tier | 220–300 | 0.61 | 0.32 | 0.90 |
| 3rd tier | > 300 | 1.07 | 0.32 | 1.36 |

Total water pric e= Tap water price + Drainage fee*0.9

source of the Yangtze River; which constitute the basic safety guarantee of water sources in the entire city. The "X" refers to reserving 30 standby and emergency water intakes in the whole city; and the plan to establish a deep-well guarantee system for emergency groundwater supply.

If Shanghai is to meet its long-term development strategy, it should consider the effects of climate change on the city and the development of cost-effective infrastructure. These measures could include taking advantage of strong economic growth, promoting economic and urban development with more stable and efficient water systems management. Specifically, the following actions will be effective to achieve this goal.

1. Adjust measures to meet local needs according to conditions. On the basis of the present situation of the four major reservoirs, relying on the Yangtze River Delta integrated resources and environment cooperation platform, the strategic cooperation of water resources in the Yangtze River and Taihu Lake basin is planned together with Jiangsu, Zhejiang and Anhui Provinces.

2. Implement specific policies. Implementing the overall requirements of urban refined and improved management for water supply industry,[13] improve relevant laws and regulations, industry policies and standards, and strengthen supervision according to laws and regulations.

3. Improve the management mechanism. Improving the cooperative management mechanism of water sources within watersheds, regions and cities; speed up the construction of "smart water supply"; and realize all-weather, whole-process and full-coverage supervision from source rce to tap. Improving the maintenance system of water supply facilities, strengthen emergency management of water supply and water conservation management, improve public participation, and continuously improve the management level of water supply industry.


CHAPTER 7

# Consolidated discussion of and lessons learned from case studies

## 7.1 INTRODUCTION

The rapid urbanization of Bulawayo, Gaborone, Lusaka, Shanghai and Windhoek seriously affects their urban water supply. This situation is worsened by climate change, which is projected to result in reduced rainfall and available water per capita. Urban development is encroaching on surrounding rural settlements that now share the same limited water sources with the cities. Bulawayo has been growing at a rate of >2.5 per cent per annum, whilst Gaborone has been doubling each decade from 1964–1991. This growth has since slowed. In Lusaka, the annual population growth rate is 4.8 per cent, with the city population more than doubling in the past 20 years. Windhoek is following the same growth trajectory as Gaborone. Urban water demand is therefore rapidly increasing, with serious water security implications for the future. This high growth is not matched by water supply and other urban infrastructural developments and is accompanied by growth in informal settlements.

The five preceding case studies show how cities are generally grappling with increased demand for water at a time when climate change variability and rapid urbanization are exacerbating the situation. In responce to this challenge, the cities have resorted to infrastructure projects to increase supply, actions to manage demand (technical and socioeconomic), or worked on institutional reforms to enhance their capacities to manage water more efficiently. The following sections look into these actions in detail using the Framework for Urban Climate Resilience shown earlier in figure 1.11 (Tyler and Moench, 2012), especially focusing on how the cities have responded. As discussed in detail in chapter 1, the Framework consists of four key elements - systems (infrastructure and ecosystems), social agents, and institutions (laws, policies and social norms). Torabi *et al*. (2021) adds social and community, economic and political resilience; these factors are implicitly covered in the discussion here. The Framework is used only as a guide and not in the framing of the case studies. So, some information is not available or uniform across the case studies. However, the Framework gives an idea of the extent to which the cities are vulnerable and expose the gaps, or otherwise, which need to be filled to reduce city susceptibility to climate change and vulnerability and rapid urbanization. While most responses are in the conventional and traditional ways of managing water, it is more interesting to see how they have gone beyond this and to understand the underlying factors informing this response. To avoid doubt, it is not the intention or spirit of this chapter to compare the cities. Instead, the objective is to highlight issues and successes where they exist. The chapter also highlights some best practices from other cities and regions that are currently not used in the cities studied.

## 7.2 STRENGTHENING INFRASTRUCTURE AND ECOLOGICAL SYSTEMS

### 7.2.1 Traditional measures to boost water supply

Climate change is projected to result in temperature increases which will also accelerate evapotranspiration rates, which currently range around 1,300–2,300 mm/year for the four African cities. This significantly reduces dam yields in semi-arid areas (Bulawayo, Gaborone, Windhoek) and even in wetter cities like Lusaka. Storage and transmission losses are going to be higher unless solutions to curtail these are introduced. In response, Bulawayo and Gaborone are no longer using shallow dams with high volume-to-surface area ratios. They also prefer to use lined channels for bulk water conveyance.

Bulawayo, Gaborone and Windhoek depend on multiple sources of water (mainly dams and some boreholes) managed by different water authorities. These cities do not have complete autonomy in planning and financing crucial water infrastructure. Thus cooperation with other agencies is crucial for their efficient water supply. Bulawayo and Gaborone have six dams each, fed from different catchments. The dams were constructed over 30 years ago, except for the Dikgatlhong Dam built in 2012 to supply Gaborone. This seeming pause in dam construction may be due to the exhaustion of nearby sources. For example, the Letsibogo and Dikgatlhong Dams are 360–400 km north of Gaborone. In addition to this, there will be boreholes and piping of water from distant sources, such as the Zambezi River, which is 900 km north of Gaborone. Bulawayo is currently constructing the Gwayi-Shangani Dam and a 245-kilometre pipeline to convey water to the city. With such distant and expensive sources of water supply, the marginal cost of supplying water may become unaffordable to most consumers.

Given that groundwater yields in semi-arid areas are limited, aquifers must be utilized with the upmost care. Except for Lusaka, the other three African study cities have limited use of groundwater in their supply mix: in Bulawayo it is 10 per cent, Gaborone ~0 per cent, Lusaka 60 per cent and Windhoek 10 per cent. The noted practice is to resort to groundwater only in critical times, thus allowing depleted groundwater resources to recover. Windhoek successfully uses wastewater for recharging groundwater – a process sometimes called water banking or managed aquifer recharge. Experience from elsewhere shows there is potential to increase groundwater recharge in urban areas by usinh porous pavements, infiltration ditches and ponds (Radcliffe, 2019).

Supplying adequate water to informal or unplanned settlements is a serious challenge facing many African cities (Rakodi, 2016). In Lusaka the impact of unplanned settlements is significant and bears on water supply services. The adverse effect of informality on willingness to invest is also important, as city authorities rarely recognize these settlements (Richmond *et al*., 2018). The informal part of the city does not directly contribute to revenues, yet it demands city services (Rakodi, 2016). The city is, therefore, denied the advantages of economies of scale as it ends up formally dealing with fewer customers. Nearly 70 per cent of residents in Lusaka live in unplanned settlements, which are supplied by informal services: kiosks, standpipes or mobile water vending. In Bulawayo, there are no informal settlements per se. However, the Government built the Garikai and Hlalani Kuhle Housing Scheme in Cowdary Park devoid of urban services such as direct household-metered water supply, sewerage, roads and stormwater drainage. Informal settlements mainly rely on water vendors and shallow wells. Wells in an urban set-up potentially expose residents to waterborne diseases such as cholera, typhoid and dysentery as reported by Phiri (2016) in Zambia and Chikeya (2018) in Zimbabwe.

Self-supply of water in Lusaka is prevalent because of shallow groundwater levels, although this practice presents pollution challenges. Self-supply of water in Lusaka is prevalent because of shallow groundwater levels, although this practice presents pollution challenges. The unlined pit latrines and faulty septic tanks contaminate groundwater around the city, with unplanned areas like Kanyama and George Compound reportedly affected. There are Community Managed Water Trusts, collectively serving nearly 1 million people in Lusaka's unplanned settlements. In Bulawayo, Gaborone and Windhoek, self-supply is limited and served mainly from individual boreholes. Very little comes from shallow wells because of deep groundwater tables.

### 7.2.2 Developing alternative sources of water

The four African case studies show that the capacity to continue supplying water at current levels will be limited in the long term. The Windhoek and Shanghai case studies suggest that future solutions are going to be a mixture of cost-effective water treatment technologies combined with wastewater reuse, sea and roundwater desalination, water harvesting (rainwater, stormwater, aquifer recharge) and transboundary water sources. Bulawayo, Gaborone and Windhoek are proposing to tap transboundary river sources. Already, Gaborone gets 8,000–16,000 $m^3$/d from South Africa's Molatedi Dam.

There are further plans by the Government of Botswana to transfer water from the Chobe-Zambezi and Lesotho Highlands Water Transfer schemes. Recent studies have also shown the viability of Zimbabwe and Botswana sharing the cost of a pipeline for the Zambezi water, but there seems to be little political buy-in on a joint project (Gumindoga *et al*., 2020). A long-term forecast shows that Windhoek will need to secure guaranteed water supply, either from the perennial Okavango River, southern dams, or desalinated water from the Atlantic Coast; depending on the costs involved. Lusaka does not have such challenges as it is already close to the Kafue River, which is adequate for its supply needs.

There are very good prospects for direct potable wastewater reclamation, as demonstrated by experiences from Windhoek and the current advancements in direct potable reuse technologies (Arnold *et al*., 2012; Du Pisani and Menge, 2013; Lahnsteiner *et al*., 2018; Roccaro, 2018). It is interesting to note that the cost of water from a DPR plant in Namibia was competitively priced at USD 0.73/$m^3$ compared with conventional sources (USD 1.01/$m^3$). Wastewater reclamation and water banking in the Windhoek Aquifer have technological inroads that present enormous lessons apart from the systematic conjunctive use of surface and groundwater sources. Dual pipelines separating semi-purified water for irrigation from domestic use is, reportedly, bearing fruit in Windhoek. Gaborone is also constructing a wastewater reclamation plant, and important lessons could also be learned from China (Lyu *et al*., 2016) and USA (Bahri and Asano, 2011). Wastewater recycling and reuse in Gaborone and Bulawayo is confined to watering public gardens, thermal power generation, firefighting and irrigating municipal open spaces and horticultural plants. Other African countries that have made significant progress in wastewater reuse include Egypt, Morocco, South Africa and Tunisia (Frascari *et al*., 2018).

What is not clear in the case studies is the use of stormwater and rainwater harvesting as alternative sources of water supply. Stormwater harvesting or stormwater reuse is the collection, accumulation, treatment or purification and storage of stormwater for its eventual reuse (Akram *et al*., 2014). Rainwater harvesting involves collection and storage of rainwater that runs off rooftops, parks, roads, open grounds, *etc* (Kinkade-Levario, 2007). This water can either be stored or channelled to recharge groundwater. Stormwater harvesting deals with collection of run-off from creeks, gullies, ephemeral streams and other ground conveyances. This can include surfaces such as roads or parking lots, parks, gardens and playing fields. The water from stormwater and rainwater harvesting can, therefore, improve the availability of water to meet the huge supply gap in the case studies of the four African cities. However, the economic and technical viability of these systems in different hydrological settings needs to be assessed first. Successful examples of stormwater harvesting are found in South Africa (Fisher-Jeffes *et al*., 2017) and Australia (Day and Sharma, 2020). Those for rainwater harvesting are in Tanzania (Mtanda *et al*. 2021) and South Africa (Kahinda *et al*., 2010).

The Conference of Parties (COP26) climate conference in Glasgow, Scotland, showed a global shift in climate issues and the greener options nations are taking for the future. This also means African cities have to adapt and "green" their water supply infrastructure by, for example, applying solar desalination, green sources of power for pumping water and recovering energy from wastewater. Successful examples of such green water supply systems are given by Laitinen *et al*. (2020) in Finland and by Masi *et al*. (2015) in India, Italy andTanzania. Pamukcu-Albers *et al*. (2021) argued that green infrastructure offers a wide range of ecosystem functions and services essential to the well-being of humans and urban sustainability; contributing to physical and mental health of urban dwellers during COVID-19 lockdown periods.

### 7.2.3 Measures used to reduce water demand

Water is a finite resource and only so much can be done to stretch its use. Managing demand is therefore crucial, especially in water-scarce areas. The average water consumption levels per capita shown in table 7.1 do not sufficiently reflect the scarcity levels in some of these cities. Lusaka and Shanghai are in areas close to large rivers and in comparatively high rainfall areas. However, Shanghai uses nearly half of that by Lusaka per capita. International best practice recommends a figure of about 100 L/cap.d (Berg and Danilenko, 2011). A lot can be done to reduce water use and demand, apart from looking for alternative water supply sources. There are other factors that affect water use, such as residential development type and lifestyles. There is evidence that technologies used in industry and household appliances play a central role in reducing water consumption in Shanghai (Huang, 2016). There are available on the market toilet kitchen, laundry and washing appliances that use far less water than traditional ones (Tam *et al*., 2021), and these are not currently mandatory in the African cities mentioned in this report. Advanced water supply technology is also reducing the cost of water. In this regard, the Shanghai case study shows frequent

**Table 7.1: Average per capita water consumption levels in the case study cities**

| City | Water Consumption Level, L/cap.day | Average Cost of Water, USD/m$^3$ |
|---|---|---|
| Bulawayo, Zimbabwe | 108 | 0.75 |
| Gaborone, Botswana | 190 | 1.54 |
| Lusaka, Zambia | 244 | 0.50 |
| Windhoek, Namibia | 150 | 1.20 |
| Shanghai, China | 123 | 0.50 |

upgrading of water treatment plants and modernization of the water distribution system.

Bulawayo has digitized its water supply network and mapped it in a Geographic Information System (GIS) environment. This has enabled it to divide the network into district-metered areas (DMAs) and to target such areas for extended-period simulations and pressure management. Similar developments have also been reported in Gaborone. Controlling pressure helps in reducing water use and also in controlling water losses (Ociepa *et al*., 2019). Technical efforts are also complemented by accessible call centres and social media platforms (Facebook, Twitter and WhatsApp), which allow residents to interact with councils and to report and monitor water-related complaints in a timely fashion.

Besides technical measures, the water demand management strategy in Bulawayo, Gaborone and Windhoek mainly consists of policy instruments (including rising block tariffs), water rationing, and public awareness campaigns. In Bulawayo, the first block of up to 5 m$^3$/month is supplied as free basic water to enable the poor to access water, which conforms with the constitutionally guaranteed human right to this resource. Subsequent blocks are charged at very punitive rates to encourage water use efficiency. While this sounds to be a good policy, it does not benefit the poor living in informal settlements who do not have a piped network for any measurement of the usage. It often benefits those in medium- and high-cost residential areas who are connected to the network.

Through concerted efforts to educate residents to reduce their water use and consumption, it has been possible for these African case study cities to suppress demand to around 70 per cent of unrestrained demand levels and keep it that way even in years of plentiful rains. The mandatory use of water-efficient technologies and benchmarking water use to international best practices (Berg and Danilenko, 2011; Danilenko *et al*., 2014) shows potential in industries and high-income urban areas where water consumption is highest. However, the Coronavirus disease (COVID-19) situation is certainly going to be a driver of future uses of water and is already changing lifestyles and hygiene behaviour (Echegaray, 2021). Its impact on water demand will become clearer with time.

## 7.3 CAPACITY OF AGENTS TO DEVELOP ADAPTIVE RESPONSES AND MAINTAIN SUPPORTIVE URBAN SYSTEMS

Agents are actors in cities that include individuals (for example, farmers, consumers); households (as units for consumption, social reproduction, education, capital accumulation); and private and public sector organizations (government departments or bureaus, private firms, civil society organizations). Key capacities that contribute to agent resilience include responsiveness, resourcefulness and the ability to learn new skills, internalize past experiences, avoid repeated failures and innovate to improve performance (Diduck, 2010).

Zimbabwe has a case of high-service standards and poor affordability (Nhapi, 2015), which presents a serious threat to service sustainability. Since the economic downturn beginning 2001, Zimbabwean cities have entered into a vicious cycle of service decline, which is difficult to reverse (UCAZ, 2017). As a result, the water service delivery chains have collapsed (Chigudu, 2019). As typified by Bulawayo, non-revenue water is averaging around 40 per cent and bill collection efficiency is around 28 per cent. According to Water and Sanitation

Program (2011) and Van den Berg and Danilenko (2017), service standards might need to be lowered, at least in the interim, to match affordability and improve service coverage.

As discussed earlier, the cost of new water sources will, increasingly, become prohibitive. The collection of billed revenues is a challenge due to varying reasons, including organizational efficiency and affordability. In addition, non-revenue water at 41 per cent for Bulawayo, 15 per cent for Gaborone and 14 per cent for Windhoek poses serious threats to service efficiency and financial sustainability in Bulawayo. Pre-paid water meters and other information and communications technology innovations to improve billing and revenue collection have been used in Gaborone and Windhoek. This has improved revenue collection. However, pre-paid meters (including automatic meter reading and instant billing, use of electronic payment platforms) were rejected outright by consumers in Bulawayo because of current unreliable supplies. Where available, data show poor city council budgetary allocations for maintenance in favour of costly repairs.

New water projects are now coming in the form of huge infrastructure projects running into hundreds of millions of United States dollars funded by either the national government or loans provided by the private or international development banks (Flyvbjerg, 2014). There are emerging concerns about the financial impact of these large infrastructure projects on local city economies (Ehlers, 2014). Botswana's ability to build several dams, a water carrier pipeline and import raw water from neighbouring South Africa may be attributed to enduring and steady revenues from mineral resources and prudent use of the earnings. In Zimbabwe, the Government is funding the ongoing construction of the Gwayi-Shangani Dam. Likewise, the Zambian Government is funding the construction of a second water treatment plant and a subsequent new pipeline from Kafue to Lusaka, the nation's capital. Shanghai is doing well financially and is thus able to fund huge capital projects.

It can be argued that future water management requires a radical shift in management paradigm at the council and utility and water resource levels (Kiparsky *et al*., 2013; Hoffmann *et al*., 2020). The future will be dominated by the two issues of water resources stewardship and water demand management rather than huge and inflexible capital development works (Chapin III *et al*., 2009). The principles of Integrated Urban Water Management (IUWM) are showing promising results as currently piloted by the Africa Ministerial Council on Water (Heaney, 2000; Brikké and Vairavamoorthy, 2016; Kirshen *et al*., 2018). The IUWM pilots in the Southern African Development Community (SADC) region focused on Kinshasa city in the Democratic Republic of Congo and Marondera municipality in Zimbabwe. IUWM is an emerging approach for urban water utilities to plan and manage water systems to minimize their impact on the natural environment, to maximize their contribution to social and economic vitality and to engender overall community improvement (Bahri, 2012). The logical starting point for adopting the IUWM approach is strategic planning and physical master plans (Mitchell, 2006; Parkinson *et al*., 2010). A systems approach is followed with system boundaries wider than those commonly used in urban water management, and includes the entire urban water cycle as well as sludge disposal, materials consumption, energy consumption and agriculture.

Some SADC member countries have committed to developing water use efficiency plans (Schreiner and Baleta, 2015) and countries like Botswana are quite advanced in this respect. The World Health Organization and the International Water Association are also working together to promote climate-resilient Water Safety Planning; South Africa and Tanzania are the pilot countries in the SADC region (IWA, London). Other regional countries are following suit and Bulawayo is currently in the process of preparing one. Water Safety Planning is a comprehensive risk assessment and risk management approach that encompasses all steps and stakeholders of the water supply system from catchment to consumers (Davison *et al*., 2009) and, therefore, reinforces the IUWM approach.

In the case of Bulawayo, Gaborone and Windhoek, transboundary rivers will play a key role in their future water supply mix. The experience in negotiating and managing these complex supply arrangements is crucial to water security in the SADC region as sole dependence on local water sources in arid to semi-arid setups are limited. Effective project management requires that projects are undertaken as a total package (holistic approach) to avoid delays resulting from omissions (Westland, 2007). All aspects of the project from conceptualization to final implementation should be well thought out and documented (Cleland, 2007). This comprehensive planning could be a challenge in the region as the case studies show a number of discrete and incremental projects in response to emergency needs. Also important is the need to prepare climate risk plans for each city based on comprehensive climate modelling (Saja *et al*., 2021).

## 7.4 TACKLING INSTITUTIONAL FACTORS THAT CONSTRAIN AGENTS' EFFECTIVENESS

Institutions are the rules or conventions that constrain human behaviour and exchange in social and economic transactions. They may be formal or informal and are created to reduce uncertainty, maintain the continuity of social patterns and social order, and stabilize forms of human interaction in more predictable ways (Tyler and Moench, 2012). Institutional characteristics that support resilience include clear rights and entitlements to use key resources or access urban systems, transparent, accountable and responsive decision-making, and facilitation of the generation, exchange and application of new knowledge (MacClune and Optiz-Stapleton, 2012).

### 7.4.1 Policies, legal frameworks for water supply and climate change

Water reforms in the SADC region have produced several water management instruments such as the SADC Protocol on Shared Watercourses, the Regional Water Policy, the Regional Water Strategy, the Regional Strategic Action Plans on IWRM, and the SADC Climate Change Strategy and Action Plan (Fatch *et al*., 2010; Dirwai *et al*., 2021). The SADC Protocol on Shared Watercourse Systems was signed in 1995 to harmonize water management in the 15 international river basins. The four African case study countries have developed their water resources plans based on the IWRM principles as explained in van der Zaag and Savenije (2004). These include recognition of fresh water as a finite and vulnerable resource, participatory management involving users, planners and policymakers at all levels; the centrality of the role of women in water management; and recognition of water as an economic good. The case study countries have also improved their planning and regulatory systems at national and city levels. For example, Botswana has the National Master Plan for Wastewater and Sanitation of 2003 and the National Water Master Plan Review (NWMPR) of 2006 and the National Water Policy of 2016. Zimbabwe developed its National Water Policy in 2013 and Climate Policy in 2015 and is currently developing its National Water Resources Master Plan. Zambia has an independent water sector regulator, which is generally regarded as a leading example in the region while Zimbabwe is establishing its water sector regulator. Mainstreaming of climate change in urban water management is appreciated in these policies and strategies but is still in its infancy.

The African study countries have climate policies and strategies and have been developing national and local adaptation plans, in line with UNFCCC requirements (Kim *et al*., 2017). They also have disaster risk reduction policies and mechanisms and have environmental management agencies that control and monitor environmental pollution, including water quality. At city level, there are by-laws on water and wastewater management. The water supply function is carried out by the city council, a government agency or a corporatized public company. Private players and NGOs are allowed to come in as water service providers with the city council remaining as service authority. Access to water in informal settlements largely remains a challenge due to the legal status of people in these areas. However, governments are beginning to make concerted efforts to ensure no one is left behind through their human settlement policies and programmes (Sjöstedt, 2011; Matamanda, 2020). The use of a rising block tariff system in the case study cities is also meant to improve access to water for the poor households that are connected to the network. The involvement of women in decision-making regarding water-related issues is facilitated by quarter systems from national (national agency), local (city council, catchment councils), down to water-point user committees.

The study cities have generally shown a high capacity to engage the political leadership and get their water needs met, although Bulawayo struggled in the past before the central Government embarked on the Gwayi-Shangani project in 2016 with zeal and purpose. Politics is about power which is embodied in the ability to win visible contests, set the policy agenda, or promulgate an ideology that favours a particular set of interests (Lukes, 2005). Political resilience manifests itself through the interplay of political will, leadership, commitment, community support, multilevel governance, and policy continuity. The IUWM philosophy requires collective decision-making in the allocation of water by the stakeholders such as city councils, farmers, miners and institutions. The sharing of water (surface and ground) with farmers brings in its own pressures, including political power (Swatuk, 2005; Mukwada *et al*., 2021). During drought periods the city has to share the limited water available with farmers, but urban, industrial and mining sectors are prioritized. This scenario shows the practical challenges of trying to decouple urban water supply from agriculture and politics.

The regular collection of water quality and quantity-related data remains a challenge in studied cities. Often the requisite infrastructure is missing or poorly maintained. Rarely is data processed and communicated to stakeholders through platforms such as websites, social media, newsletters and bulletins. Rainfall and other meteorological data are sold at exorbitant prices, which hamper their use by private individuals and researchers, yet data is readily available from archives of developing countries. Data is crucial in building adaptive capacity and cities' resilience. The websites of the cities are not regularly update, therefore do not provide reliable information. The publication of contact details of councillors and key personnel, together with the use of toll-free telephone numbers, improves transparency and communication with the public. The online availability of key council documents such as annual reports, financial statements, policies, by-laws, service application forms contributes to an informed citizenry.

The formation of project steering committees with representation from key stakeholders has helped prevent most of the potential problems across sectors and interagency red tape in Lusaka. The water sector key stakeholders and experts in Namibia (including those in Windhoek - NamWater, the Ministry of Water, the Cabinet Committee on Water Security and City of Windhoek, wet industries, the Basin Management Committee, stakeholders and water users) have worked as a team and combined efforts in planning water resources. This demonstrates IWRM in action.

Private sector involvement in water sector planning and implementation as well as the existing Public-Private Partnerships, has had remarkable success in City of Windhoek water supply. However, it has had mixed results in South Africa (Dithebe *et al*., 2019), whilst in the USA it has been responsible for the supply of up to 14 per cent of household water and sanitation services (Davis, 2005). After reviewing institutions for urban water supply in Africa south of the Sahara, Adams *et al*. (2019) recommended innovative governance and institutional arrangements that blend the strengths of public, private and community-based water supply models.

### 7.4.2 Capacity strengthening of city departments or water utilities

Literature shows that the nature and scale of the projects to increase water supply to the four cities studied require highly skilled staff (Flyvbjerg, 2014). At a regional level, SADC has been running a capacity development programme for IWRM through WaterNet and the SADC Groundwater Management Initiative. There are also smaller versions of the WaterNet programme, such as the Southern African Science Service Centre for Climate Change and Adaptive Land Adaptative Land Management - IWRM postgraduate programme at the Namibia National University of Science and Technology. The programme involves Angola, Botswana, Namibia, South Africa and Zambia. The city councils have been also sending staff on professional short courses and postgraduate studies. This has made them receptive to new technologies, techniques and strategies to improve management of urban water.

One of the critical lessons learned during the implementation of improvement projects in Lusaka is the need for international organizations involved to transfer knowledge and skills to local staff as some of the large projects happen once in a long time and capacity could be built within the country to undertake some of these major and complex projects.

## 7.5 COMPARATIVE LESSONS ON URBAN WATER SECURITY FROM CHINA

The case study from China shows that Shanghai has consistently collected and maintained comprehensive water-related data for a long time and this is used for evidence-based planning. Institutions for water resources management are well-resourced and effective; resulting in consistent and predictable developments which are guided by appropriate urban planning norms. The use of information communication technologies in water treatment, network operation and revenue collection is advanced and helps to reduce costs and enhance revenue collection. The raw water sources, network systems and water treatment design and operations use modelling software and are optimized to enhance efficiency. The designs take into account climate resilience and the need to reduce carbon emissions with specific targets and vision for the year 2035. The link between industry and research and development institutions is robust. This ensures newly developed technologies have takers and relevance. As a result, their water treatment plants have been constantly upgraded over time as reflected in Shanghai reducing its treatment plants from 105 in 2010 to 37 by 2019.

In China, urban planning standards are strictly enforced and these are coordinated with long-term engineering and water supply plans and strategies. This ensures that all new developments have adequate water supplies. China also has a very strong regulatory framework to guide the water supply sector and strong institutions to enforce these regulations. An example is the way they regulate groundwater use because of the sensitive nature of high-rise buildings in coastal areas. In Shanghai, there is conjunctive use of two major rivers and groundwater and clear operating rules for this are applied. China displays a high degree of discipline and commitment in the way it approaches developmental issues, which can benefit African countries, immensely.

## 7.6 SUMMARY OF WATER SECURITY WITHIN BUILDING URBAN CLIMATE RESILIENCE

Tables 7.2 to 7.4 show the extent to which the concept of urban climate resilience is implemented in the studied cities. In the absence of a thorough climate and disaster vulnerability assessment of the respective towns, the available data show many factors that contribute to city resilience are somewhat present, and that the cities need to learn from each other. The tables show that the following are the major constraints in these cities: financial resources, no equitable access to water by the poor and vulnerable groups, poor urban planning and corporate management systems, no knowledge management, and lack of transparency and accountability. These key shortcomings are highlighted in italics in the tables.

**Table 7.2: Analysis of resilience of infrastructure and ecosystems in case study cities**

| System Characteristic | Performance Description | Findings in the Case Study Cities |
|---|---|---|
| Flexibility and diversity | The system can meet service needs under a wide range of climate conditions. Key elements are spatially distributed and can substitute for each other but are functionally linked | Multiple, geographically distributed surface and groundwater sources.<br>District metered areas established to manage water pressure and leakages.<br>Pumping stations and service reservoirs in multiple sites with overlapping service.<br>Water demand management measures implemented to ensure water is used efficiently.<br>Wastewater reuse to augment potable and non-potable uses.<br><u>Capacity to invest in water supply systems is a major constraint.</u><br><u>The incorporation of climate change in planning and design of infrastructure is limited.</u> |
| Redundancy and modularity | Spare capacity to accommodate unexpected service demand or extreme climate events.<br>System components and pathways provide multiple options or substitutable components for service delivery | Reservoir storage capacity oversized to exceed demand under drought conditions.<br>Withdrawal rate from aquifers regulated to ensure it does not exceed groundwater recharge.<br>New dams (e.g., Gwayi-Shangani Dam) with storage sufficient to buffer annual variability or other supply disruptions.<br>Diesel generators and dedicated power supplies used as backup systems for water pumping<br>Rainwater harvesting systems to supplement domestic water supply. |
| Safe failure | Failure in one part of the system will not lead to cascading failures of other elements or related systems. Key service delivery can be maintained even under failures | The systems protect and regularly monitor water quality from the source, treatment plant, service reservoirs and the distribution network.<br>Failure of one pumping station does not lead to distribution system failure.<br>Distribution network interlinked, so local failure will not cause major service interruptions. |

**Table 7.3: Analysis of the resilience of agents in the case study**

| Agent Capacities | Performance Description | Findings in the Case Study Cities |
|---|---|---|
| Responsiveness | Ability to organize, or reorganize in a timely manner; ability to identify, anticipate, plan and prepare for a threat, disruptive event or organizational failure; and to respond quickly in its aftermath | City councils have planning, engineering and other capabilities for water management. <u>However, these personnel need continuous professional development.</u><br>Some councils have call centres, social medial platforms, service charters and benchmark times for responding to customer complaints.<br>Residents' associations, industrialists and NGOs proactively lobby council, central government and market actors to improve service quality.<br><u>The monitoring of system condition is limited by budgetary allocations and there are limited budgets for maintenance (leak detection, supply sources).</u> |
| Resourcefulness | Capacity to mobilize assets and resources for action. This includes the ability to access financial and other assets, including those of other agents and systems, through collaboration | To varying degrees, city councils have legal authority, financial and technical resources that they can deploy effectively <u>if they can improve the collection of water revenues.</u><br>City councils proactively work with the private sector, NGOs and central government to address issues that cross sectors or scales.<br>Consumers and NGOs mobilize support to address water quality or reliable supply, even when distribution systems fail<br>Developing partners and NGOs assist in water supplies in informal settlements. |
| Capacity to learn | Ability to internalize past experiences, avoid repeated failures and innovate to improve performance. This includes the capacity to build and retain knowledge over time | Past experience is incorporated into planning and implementation activities.<br>Water supply modelling is used for planning, projections and analysis of scenarios.<br>Water master plans are routinely revisited and refined by experts based on emerging information and development trajectories.<br><u>In some cases, user groups rarely access water resource information and therefore lack the capacity to use it as a basis for advocacy.</u><br><u>Lacking enough mechanisms to ensure knowledge and technology transfer, especially for large water infrastructure projects and transboundary water negotiations.</u> |

## 7.7 SYNTHESIS OF LESSONS LEARNED TO ENHANCE URBAN WATER SECURITY IN CONTEXT OF CLIMATE CHANGE

The five studied cities are showing the benefits of effective planning and professional management of the urban water supply function. Consistently, the following factors seem to underlie any success stories observed:

i. A technically and financially strong water utility or city department that can undertake long-term planning (both urban planning and water supply master plans) and mobilize resources and stakeholders in all developmental processes.

ii. A strong water resource function that is supported by the national government in raising financial and technical resources for large-scale and multiple projects.

iii. Supportive national government that creates an enabling environment through standards, policies and regulations. This includes policies on water supply, access to water, urban planning and regularization of informal settlements.

iv. Promotion of climate-resilient urban water development through applicable policy instruments, climate data collection networks, adaptation frameworks at national and city levels that address water security, capacity development and financing.

### Table 7.4: Analysis of the resilience of institutions in the case study

| Institutional Features | Performance Description | Findings in the Case Study Cities |
|---|---|---|
| Rights and entitlements | Structures of rights and entitlements do not systematically exclude specific groups from access to critical systems or capacities. They enable groups to form and act, and foster access to basic resources | Water supply systems do not make potable water widely available to all social groups in the city, especially the urban poor and informal settlements.<br>The use of rising block tariff structures ensure affordability.<br>In areas not supplied by the city council or water utility, NGOs have mobilized community groups to raise funds and implement water management activities.<br>All stakeholders have legal or constitutional rights with regard to water resources, access to information and participate with other agents in water-related policy deliberations or other initiatives.<br>Water allocation and investment processes are guided by clear rules and legal procedures which involve stakeholder consultations.<br>Water providers are accountable to legitimate government agency and regulator and can be sanctioned for unjustified actions. Formal or informal systems are in place to mediate water-related disputes as they emerge, whether they involve public or private agencies./ |
| Information | Agents have access to relevant information in order to determine effective actions and to make strategic choices for adaptation | City councils and government agencies have access to and use current global scientific information and knowledge in planning water supply<br>City councils have by-laws with basic standards for water supply norms (quantity, quality, reliability, affordability) and the protection and maintenance of the ecosystems that deliver water services. |
| Application of new knowledge | Institutions encourage inquiry, application of evidence, critical assessment and application of new knowledge | Water utilities and city councils rarely provide financial support for applied research in its water supply issues<br>No dedicated research fund for water and climate change.<br>City council, NGOs and the private sector work together to develop innovative approaches to managing water resources under changing climate conditions. |

v. A strong private sector and civil society involvement in the planning, awareness raising and mobilization of financial resources, including involvement in informal settlements.

vi. Use of scientific data and information and communications technology to improve planning, design, operation and revenue collection for the city or water utility.

vii. An innovative and entrepreneurial culture within the water utility or city council that spurs them to experiment and try out new methods, techniques or technologies, and hence improve service efficiency.

viii. A learning organization that is flexible and able to adapt and respond to new knowledge.

CHAPTER 8

# Conclusions, recommendations for urban water security

## 8.1 OVERALL CONCLUSIONS FROM THE CASE STUDIES

The following conclusions can be drawn from the five case studies in this book:

i. Under a business-as-usual scenario, climate change and variability and rapid urbanization will continue to impose a severe strain on the water supply situation, well into the future, in the four studied Africa cities.

ii. As the available water per capita and affordability continue to decline, the future lies more in water-demand management and looking for new sources of this compound.

iii. Peri-urban developments and informal settlements are an integral part of urbanization in Africa, so sustainable water supplies requires innovative forms of provision to these areas.

iv. African countries lag in filling technological gaps in providing efficient water supplies. This deficiency has resulted in inadequate service coverage and inefficient, unsustainable services. Partnerships with rapidly developing economies like China would help, greatly, help alleviate this problem.

## 8.2 RECOMMENDATIONS TO ACHIEVE WATER SECURITY IN RAPIDLY GROWING CITIES AGAINST THE BACKDROP OF CLIMATE CHANGE

The following recommendations could help improve the resilience of the case studies in the face of climate risks and rapid urbanization:

i. A comprehensive assessment of the vulnerability of systems, agents and institutions to climate risks and rapid urbanization needs to be carried out to aid better understanding of the situation on the ground. Several assessment tools and guidelines have been developed recently. By methodically examining systems and how agents, system fragility, and institutions regulate system access, the entry points for building resilience can be correctly identified. The cities can use this assessment to refine and develop an urban climate resilience framework that can be scaled up in the region and beyond.

ii. The five case study cities have complementary strengths that can benefit each other. Forming and formalizing a peer learning network would enable the cities to share experiences, knowledge and best practice.

iii. Wastewater reuse, in its various forms, can boost water supplies in the four African cities. This solution should be scaled up as much as possible.

iv. Slums and informal settlements are existential problems that must be acknowledged and tackled through sound strategic and urban planning. The characteristics of these informal settlements are determined by local conditions (for example, geographical, demographic, political, economic and social factors). Meantime, local models of water supply to these areas need to be developed in partnership with the communities, non-governental organizations and other stakeholders.

v. Comprehensive planning of water supplies at different levels (water resources, city level, physical planning, water master plans) and enforcement of regulations and legislation, with support from all stakeholders, appear to be working in some of the cities. These efforts can be improved and scaled up. Adopting the Integrated Urban Water Management philosophy will attend to this situation.

vi. The trust and reliance on sound data and science in guiding planning and management of water supplies in China, though obvious, is a vital lesson for African cities to follow. Governments can complement this by developing enabling policies and suitable conditions for their enforcement.

vii. A separate study on how the four African cities manage wastewater would help complete the picture of the urban water cycle. This new study would also provide insights into how the water resources in the cities could be optimized given rapid urbanization, climate change and variability.

## 8.3 WAY TO BUILD REGIONAL URBAN WATER SECURITY

This publication was based on a desk study of four selected cities in Southern Africa and Shanghai, China. The study raises many interesting issues that can be the basis of further and focused inquiry, which is of interest to many partners in this project: the city councils themselves, central governments, UN-Habitat, and the Southern Africa Development Community. The cities have acted to build climate resilience along different pathways, depending on their unique problems and their societal aspirations. A detailed participatory study that covers wastewater and solid waste, looking at spatial and temporal vulnerabilities, is required so that specific actions can target specific vulnerabilities. The underpriviledged in formal and informal settlements are of particular interest. The mapping of vulnerabilities and engineering studies can be done together so that climate vulnerabilities of infrastructure and ecosystems can be better undertstood. UN-Habitat and Tongji University can formally involve local universities in such studies. Such inclusion would build and sustain the knowledge so gained.

To facilitate the study suggested above, there is a need to formalize the network of the five cities so they can meet regularly at different levels, online and at physical meetings, to share experiences and peer review each other. The network can work to adapt and improve existing urban climate resilience frameworks and develop monitoring benchmarks based on that framework. With time, the network can add other cities and assist them in improving their systems, agent capacities and institutional efficiencies. The network can also assist the cities in reviewing new and existing water management and climate-resilient plans.

## 8.4 WAY FORWARD TO BUILD REGIONAL URBAN WATER SECURITY

This publication was based on a desk study of four selected cities in Southern Africa and Shanghai, China. The study raises a lot of interesting issues that can be the basis of further and focused inquiry which is of interest to many of the partners in this project: the city councils themselves, central governments, UN-Habitat, the Southern Africa Development Community. The cities have acted to adapt and build climate resilience in different pathways, depending on the unique problems they face and their societal aspirations. A detailed participatory study is required that covers wastewater and solid waste and looking at spatial and temporal vulnerabilities so that specific actions can target specific vulnerabilities. Of particular interest are the urban poor in formal and informal settlements. The mapping of vulnerabilities can be done in conjunction with engineering studies to understand, better, the climate vulnerabilities of infrastructure and ecosystems. UN-Habitat, in partnership with Tongji University, can formally add local universities in such studies in order to build and sustain the knowledge so gained.

To facilitate the study suggested above, there is a need to formalize the network of the five cities so they can meet regularly at different levels, using online and physical meetings, to share experiences and peer review each other. The network can work to adapt and improve existing urban climate resilience frameworks and develop monitoring benchmarks based on that framework. With time, the network will be adding other cities and assisting them to improve their systems, agent capacities and institutional efficiencies. The network can assist the cities in reviewing new and existing water management and climate resilient plans.

# References


**CHAPTER 1:**

Adger, W. Neil., and others, "Social-ecological resilience to coastal disasters". Science, vol. 309 No. 5737 (2005), pp.1036–1039.

Africapolis. Visualise Urbanisation n Africa. Available at https://africapolis.org/en

Ajjur, Salah. B., and AlGhamdi, S. G., "Global hotspots for future absolute temperature extremes from CMIP6 models", Earth and Space Science, vol. 8 No. 9, (2021), e2021EA001817.

Alaazi, Dominic A., and Gamel A. Aganah,. "Understanding the slum–health conundrum in sub Saharan Africa: a proposal for a rights-based approach to health promotion in slums", Global

Health Promotion, vol. 27, No. 3 (2020), pp. 65–72.

Aloysius, Noel. R., Sheffield, J., Saiers, J. E., Li, H., and Wood, E. F., "Evaluation of historical and future simulations of precipitation and temperature". In central Africa from CMIP5 climate models, J. Geophys. Res. Atmos, vol. 121, (2016), pp.130–152. Available at DOI: 10.1002/2015JD023656.

Anderson, Pippin. M., Okereke, C., Rudd, A., and Parnell, S. (2013). Regional assessment of Africa. In Urbanization, biodiversity and ecosystem services: Challenges and opportunities (pp.453–459). Springer, Dordrecht.

Asian Development Bank (2014). Urban climate change resilience: A synopsis, Manila, Philippines

Avis, W. R. (2016). Urban Governance (Topic Guide). Birmingham, UK: GSDRC, University of Birmingham.

Awumbila, Mariama, "Drivers of migration and urbanization in Africa: Key trends and issues", International Migration, vol. 7, No. 8, (2017).

Baker, Judy. L. (ed.). Climate Change, Disaster Risk, and the Urban Poor: Cities Building Resilience for a Changing World. Washington, D.C.: World Bank Publications, 2012.

Balaban, Osman. "Climate change and cities: a review on the impacts and policy responses", METU Journal of the Faculty of Architecture, vol. 29, No. 1, (2012), pp. 21–44.

Beuel, Sonja., Alvarez, M., Amler, E., Behn, K., Kotze, D., Kreye, C., and Becker, M., "A rapid assessment of anthropogenic disturbances in East African wetlands", Ecological Indicators, vol. 67, (2016), pp.684–692.

Biggs, Reinette., Rhode, C., Archibald, S., Kunene, L. M., Mutanga, S. S., Nkuna, N., and Phadima, L. J., "Strategies for managing complex social-ecological systems in the face of uncertainty: examples from South Africa and beyond", Ecology and Society, vol. 20, No. 1, (2015).

Blunden, Jessica., Hartfield, G., Arndt, D. S., Dunn, R., Tye, m., Blenkinsop, S., and Jacobs, S., "State of the Climate in 2017", Bulletin of the American Meteorological Society, vol. 99, No. 8, (2018), Si-S310.

Boadi, Kwesi., Kuitunen, M., Raheem, K., and Hanninen, K., "Urbanisation without development: environmental and health implications in African cities", Environment, Development and Sustainability, vol. 7, No. 4, (2005), pp. 465–500.

Brian Donegan (2019). "El Niño Conditions Strengthen, Could Last Through Summer". The Weather Company. Accessed 20 August 2021.

Byakatonda, Jimmy., Parida, B. P., Moalafhi, D. B., Kenabatho, P. K., and Lesolle, D., "Investigating relationship between drought severity in Botswana and ENSO". Natural Hazards, vol. 100, No. 1, (2020), pp. 25–278.

Cobbinah, Patrick. B., "Urban resilience in climate change hotspot", Land Use Policy, vol. 100, (2021) 104948.

Corburn, Jason, and Alice Sverdlik (2019). Informal Settlements and Human Health. In Integrating Human Health into Urban and Transport Planning, pp.155–171.

Cosgrove, William. J., and Daniel P. Loucks, "Water management: Currentand future challenges and research directions", Water Resource Research, vol. 51, (2015), pp.4823–4839. Available at doi:10.1002/2014WR016869.

David Satterthwaite and others (2018). "Responding to climate change in cities and in their informal settlements and economies". Paper prepared for the Intergovernmental Panel on Climate Change for the International Institute for Environment and Development, Edmonton, Canada, March.

Davis, Claire. L., and others (2017). Future climate change over Southern Africa., Worklist;20314 African Sun Media. Abailable at http://hdl.handle.net/10204/10085 . In South African Risk and Vulnerability Atlas: Understanding the Social and Environmental Implications of Global Change, pp. 13–25

Davis-Reddy, Claire. L., and Vincent, K. (2017). Climate Risk and Vulnerability: A Handbook for Southern Africa (2nd Ed), CSIR, Pretoria, South Africa.

De Wit, Maarten., and Jacek Stankiewicz, "Changes in surface water supply across Africa with predicted climate change". Science, vol. 311, No. 5769 (2006), pp.1917–1921.

Duit, Andreas., and Victor Galaz, "Governance and complexity—emerging issues for governance theory", Governance, vol. 21, No. 3 (2008), pp. 311–335.

Dunning, Caroline. M., Emile Black., and Richard P. Allan, "Later wet seasons with more intense rainfall over Africa under future climate change", Journal of Climate, vol. 31, No. 23 (2018), pp. 9719–9738.

Elmqvist, Thomas., Wayne C. Zipperer., and Burak Güneralp, (2015). Urbanization, habitat loss and biodiversity decline: solution pathways to break the cycle. In The Routledge Handbook of Urbanization and Global Environmental Change, pp. 163–175). Routledge.

Emilsson, Tobias., and Åsa. O. Sang, (2017). Impacts of climate change on urban areas and nature-based solutions for adaptation. In Nature-Based Solutions to Climate Change Adaptation in Urban Areas, pp. 15–27. Springer, Cham.

Fox, S. (2014). The political economy of slums: Theory and evidence from Sub-Saharan Africa. World Development, vol. 54, pp. 191–203.

Furth, Deborah. P., "What's in the Water: Climate Change, Waterborne Pathogens, and the Safety of the Rural Alaskan Water Supply", Hastings Environmental Law and Policy Journal vol. 16, No. 251, (2010).

Güneralp, Burak, and others, "Trends in urban land expansion, density, and land transitions from 1970 to 2010: a global synthesis", Environmental Research Letters, vol. 15, No. 4 (2020) 044015.

Hallegatte, Stéphane, and Jan Corfee-Morlot, "Understanding climate change impacts, vulnerability and adaptation at city scale: an introduction", Climatic Change, vol. 104, No. 1 (2011), pp. 1–12.

Herrera-Pantoja, M., and Hiscock, K. M. "Projected impacts of climate change on water availability indicators in a semi-arid region of central Mexico", Environmental Science and Policy, vol. 54, (2015), pp. 81–89.

Hope Sr, Kempe. R. (2009). "Climate change and poverty in Africa", International Journal of Sustainable Development and World Ecology, vol. 16, No. 6 (2009), pp. 451–461.

Hunt, Alistair., and Paul Watkiss, "Climate change impacts and adaptation in cities: a review of the literature", Climatic Change, vol. 104, No. 1 (2011), pp. 13–49.

Intergovernmental Panel on Climate Change (2007). Climate change 2007: Appendix to synthesis report. In A.P.M. Baede, P. van der Linden, and A. Verbruggen, eds., Climate Change 2007: Synthesis Report. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change, pp. 76–89. Geneva, Switzerland.

_________ (2012). Glossary of terms. In Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). pp. 555–564. Cambridge, UK., and New York, NY, USA. Cambridge University Press.

_________ (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer, (eds.)]. Geneva, Switzerland, pp. 151, IPCC.

Jha, Abhas. K., Todd W. Miner., and Zuzana Stanton-Geddes, eds. (2013). Building urban resilience: principles, tools, and practice. Washington D.C.: World Bank Publications, 2013.

Johnson, Michael, P. "Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda", Environment and Planning A, vol. 33, No. 4 (2001), pp.717–735.

Kathryn A. Miller, Ndoni Mcunu, Andreas Anhäuser, Aidan Farrow, David Santillo and Paul Johnston. Weathering the Storm: Extreme weather events and climate change in Africa. Greenpeace Research Laboratories Technical Report (Review) 04-2020. Available at https://www.greenpeace.org/africa/en/weathering-the-storm-extreme-weather-events-and-climate-change-in-africa (Accessed August 2021).

Kativhu, Tendai., and others (2021). The Water Sanitation and Hygiene Perspective in Response to Cyclone Idai in Zimbabwe. In Cyclones in Southern Africa, pp. 115–129. Springer, Cham.

Kessides, Christine, "The urban transition in Sub-Saharan Africa: challenges and opportunities", Environment and Planning C: Government and Policy, vol. 25, No. 4 (2007), pp. 466–485.

Kotir, Julius. H., "Climate change and variability in Sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security", Environment, Development and Sustainability, vol. 13, No. 3 (2011), pp. 587–605.

Kovacic, Zora., and others, "Interrogating differences: A comparative analysis of Africa's informal settlements", World Development, 122, (2019), pp. 614–627.

Kulabako, Robinah, N., and others. "Environmental health practices, constraints and possible interventions in peri-urban settlements in developing countries–a review of Kampala, Uganda", International journal of environmental health research, vol. 20, No. 4 (2010), pp. 231–257.

Kundzewicz, Zbigniew, W., "Climate change impacts on the hydrological cycle", Ecohydrology and Hydrobiology, vol. 8, No. 2–4 (2008), pp. 195–203.

Kusangaya, Samuel., and others "Impacts of climate change on water resources in southern Africa: A review", Physics and Chemistry of the Earth, Parts A/B/C, vol. 67, (2014), pp. 47–54.

Lafferty, Kevin. D., "The ecology of climate change and infectious diseases", Ecology, vol. 90, No. 4 (2009), pp. 888–900.

Lal, Rattan, "Carbon sequestration in dryland ecosystems", Environmental Management, vol. 33, No. 4 (2004), pp. 528–544.

Leal Filho, Walter., and others, "Assessing the impacts of climate change in cities and their adaptive capacity: towards transformative approaches to climate change adaptation and poverty reduction in urban areas in a set of developing countries", Science of the Total Environment, vol. 692, (2019), pp. 1175–1190.

Leichenko, Robin, "Climate change and urban resilience", In Current Opinion in Environmental Sustainability, vol. 3, No. 3 (2011), pp. 164–168. Available at http://dx.doi.org/10.1016/j.cosust.2010.12.014

Lesolle, D. (2012). SADC policy paper on climate change: assessing the policy options for SADC member states. SADC Secretariat, Policy, Planning, Resource Mobilisation Directorate.

Lisowski, A., Mantey, D., and Wilk, W., The Lack of Coordinated Planning and Its Impacts on Urban Sprawl, In Confronting suburbanization: Urban decentralization in postsocialist Central and Eastern Europe, pp. 225–255. John Wiley and Sons: Chichester, (2014).

Love, D., Zingoni, E., Gandidzanwa, P., Magadza, C., and K. Musiwa. Impacts on groundwater quality and water supply of the Epworth semi-formal settlement, Zimbabwe, In Diffuse Pollution of Water Resources (pp. 117–132). CRC Press, 2005.

Matamanda, Abraham, R., and Verna Nel, (2021). (Un) Healthy Cities: Reflections on Urban Public Health in Poor Neighbourhoods. In Urban Geography in Postcolonial Zimbabwe (pp. 93–118). Springer, Cham.

Mbonambi, Zinhle. "An investigation into the environmental impacts of informal settlements on water: a case of Kennedy Road informal settlement in Durban, KwaZulu-Natal", PhD dissertation, -------------, 2016.

McMichael, A. J., and others. (2003). Climate change and human health: risks and responses. World Health Organization.

Meerow, S., Newell, J. P., and Stults, M. Landscape and Urban Planning, vol. 147, (2016), pp. 38–49.

Merel, Sara., and others. "State of knowledge and concerns on cyanobacterial blooms and cyanotoxins", Environment International, vol. 59, (2013), pp. 303–327.

Miller, James. D., and Michael Hutchins, "The impacts of urbanization and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom", Journal of Hydrology: Regional Studies, vol. 12, (2017), pp. 345–362.

Moench, Marcus, "Experiences applying the climate resilience framework: Linking theory with practice", Development in Practice, vol. 24, No. 4 (2014), pp. 447–464.

Moench, M., Tyler, S., and Lage, J., eds. (2011). Catalyzing urban climate resilience: Applying resilience concepts to planning practice in the ACCCRN Program (2009–2011). Institute for Social and Environmental Transition, International.

Monzon, Andres (2015). Smart cities concept and challenges: Bases for the assessment of smart city projects. In 2015 International Conference on Smart Cities and Green ICT Systems (SMARTGREENS), pp. 1–11. IEEE.

Morchain, Daniel., and Frances Kelsey, (2016). Finding ways together to build resilience: The vulnerability and risk assessment methodology. Oxfarm GB, Oxford, UK

Morote, Álvaro. F., Olcina, J., and Hernández, M., "The use of non-conventional water resources as a means of adaptation to drought and climate change in semi-arid regions: South-Eastern Spain", Water, vol. 11, No. 1 (2019), p. 93.

Morrison, Nicky, "Playing by the rules? New institutionalism, path dependency and informal settlements in sub-Saharan Africa". Environment and Planning A: Economy and Space, vol. 49, No. 11 (2017), pp. 2558–2577.

Moser, Caroline., and David Satterthwaite, Towards pro-poor adaptation to climate change in the

urban centers of low- and middle-income countries. In R. Mearns and A. Norton, eds. Social

dimensions of climate change: Equity and vulnerability in a warming world, pp. 231–258.

Washington, D.C.: World Bank, 2010.

Mosley, Luke. M., "Drought impacts on the water quality of freshwater systems; review and integration", Earth-Science Reviews, vol. 140, (2015), pp. 203–214.

Muller, Mike. (2007). Adapting to climate change: water management for urban resilience. Environment and urbanization, vol. 19, No. 1 (2007), pp.99–113.

Nhamo, Godwell., and David Chikodzi. Cyclones in Southern Africa. Springer International Publishing, 2021.

Nyong, Anthony., and Isabelle Niang-Diop (2006). Impacts of climate change in the tropics: the African experience. In Avoiding Dangerous Climate Change, p. 235.

Olalekan, Bakare. G., "Urbanization, urban poverty, slum and sustainable urban development in Nigerian cities: challenges and opportunities", Developing Country Studies, vol. 4, No. 18 (2014), pp. 13–19.

Pamukcu-Albers, Pinar and others. (2021). "Building green infrastructure to enhance urban resilience to climate change and pandemics", Landscape Ecology, vol. 36, No. 3 (2021), pp. 665–673.

Parnell, Susan., and Ruwani Walawege, "Sub-Saharan African urbanization and global environmental change", Global Environmental Change, vol. 21, (2011), S12–S20.

Patel, Kamna (2013). TOPIC GUIDE: Provision and Improvement of Housing for the Poor. London: Evidence on Demand.

Phiri, Adrian, "Risks of domestic underground water sources in informal settlements in Kabwe-Zambia", Environment and Pollution, vol. 5, (2016), pp. 1–14.

Race, Digby., Gary W. Luck., and Rosemary Black (2010). Patterns, drivers and implications of demographic change in rural landscapes. In Demographic change in Australia's rural landscapes, pp. 1–22. Springer, Dordrecht.

Southern African Development Community. Available at www.sadc.int

Saghir, J., and J. Santoro, (2018). Urbanization in Sub-Saharan Africa. In Meeting Challenges by Bridging Stakeholders. Washington, D.C., USA: Center for Strategic and International Studies.

Shukla, Kartikeya., and others (2021). Socio-economic Assessment of Climate Change Impact on Biodiversity and Ecosystem Services. In Climate Change and the Microbiome, pp. 661–694. Springer, Cham.

Sinharoy, Sheela. S., Rachael Pittluck, and Thomas Clasen, "Review of drivers and barriers of water and sanitation policies for urban informal settlements in low-income and middle-income countries", Utilities Policy, vol. 60, (2019), 100957.

Teixeira, Edmar, I., and others, "Global hot-spots of heat stress on agricultural crops due to climate change", Agricultural and Forest Meteorology, vol. 170, (2013), pp. 206–215.

The Conversation Climate Change, Migration an Urbanisation: patterns in Sub-Saharan Africa (2 Nov 2020/an online journal). Available at https://theconversation.com/climate-change-migration-and-urbanization-patterns-in-sub-saharan-africa-149036

Tsolakis, Naoum., and Leonidas Anthopoulos, "Eco-cities: An integrated system dynamics framework and a concise research taxonomy", Sustainable Cities and Society, vol. 17, (2015), pp. 1–14.

Twigg, John. (2007). Characteristics of a Disaster-resilient community: A Guidance Note. London: DFID DRR Interagency Coordination Group.

Tyler, Stephen and Marcus Moench, "A framework for urban climate resilience", Climate and Development, vol. 4, No. 4 (2012), pp. 311–326. Avaiable at DOI:10.1080/17565529.2012.745389.

UN-Habitat (2003). Guide to Monitoring Target 11: Improving the lives of 100 million slum dwellers. Nairobi, Kenya.

________ (2015). Habitat III issue paper 22—informal settlements. New York: UN-Habitat.

________ (2021). SDG indicator metadata (Harmonized metadata template - format version 1.0). New York: UN-Habitat. Available at https://unstats.un.org/sdgs/metadata/files/Metadata-11-01-01.pdf . Accessed: 4 January 2022

United Nations Environment Programme (2011). Decoupling Natural Resource Use and Environmental Impacts from Economic Growth. International Resource Panel, United Nations Environment Programme. Sustainable Consumption, and Production Branch. UNEP/Earthprint.

Van Gelder, Jean-Louis, "Paradoxes of urban housing informality in the developing world", Law and Society Review, vol. 47, No. 3 (2013), pp. 493–522.

Weiskopf, Sarah. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., Halofsky, J. E., ... and Whyte, K. P., "Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States", Science of the Total Environment, vol. 733, (2020), 137782.

Winsemius, Hessel. C., Brenden Jongman., Ted I. Veldkamp., Stephane Hallegatte., Mook Bangalore., and Philip J. Ward, (2018). "Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts", Environment and Development Economics, vol. 23, No. 3, pp. 328–348.

World Bank. Sub-Saharan Africa. Available at https://data.worldbank.org/region/sub-saharan-africa.

Yiran, Gerald. A. B., and others. "Urban sprawl in sub-Saharan Africa: A review of the literature in selected countries", Ghana Journal of Geography, vol. 12, No. 1 (2020), pp. 1–28.

Yu, David J., Michael L. Schoon, Jason K. Hawes, Seungyoon Lee, Jeryang Park, P. Suresh C. Rao, Laura K. Siebeneck, and Satish V. Ukkusuri. "Toward general principles for resilience engineering", Risk Analysis, vol. 40, No. 8, (2020), pp. 1509–1537.

Zeleňáková, Martina., and others. "Mitigation of the adverse consequences of floods for human life, infrastructure, and the environment", Natural Hazards Review, vol. 18, No. 4 (2017), 05017002.

Zerbo, Alexandre., Rafael C. Delgado., and Pedro A. González, "Vulnerability and everyday health risks of urban informal settlements in sub-Saharan Africa", Global Health Journal, vol. 4, No. 2 (2020), pp. 46–50.

Zhang, Xiaoling, "Going green: initiatives and technologies in Shanghai World Expo", Renewable and Sustainable Energy Reviews, vol. 25, (2013), pp. 78–88.

Zhongming, Z., Linong, L., Wangqiang, Z., and L. Wei, (2020). World Cities Report 2020: The Value of Sustainable Urbanization.

Ziervogel, Gina., and Susan Parnell. (2014). Tackling barriers to climate change adaptation in South African coastal cities. In Bruce Glavovic and Gavin Smith, eds. Adapting to Climate Change, pp. 57–73. Springer, Dordrecht.

Zonta, Roberto., and others."The effect of floods on the transport of suspended sediments and contaminants: a case study from the estuary of the Dese River (Venice Lagoon, Italy)", Environment International, vol. 31, No. 7, (2005), pp. 948–958.

**CHAPTER 2:**

Aguilar, Enrich, and others, "Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955–2006", Journal of Geophysical Research: Atmospheres, vol. 114, No. D2 (2009).

Authur Maviza and Fethi Ahmed. "Climate change/variability and hydrological modelling studies in Zimbabwe: a review of progress and knowledge gaps". SN Applied Sciences, vol. 3, No. 5 (2021), pp. 1–28.

Average Chigwenya, "Low income housing problems and low-income housing solutions: opportunities and challenges in Bulawayo", Journal of Housing and the Built Environment, vol. 34, No. 3 (2019), pp.927–938.

Bosch, Stemele (2012). City of Bulawayo Water and Wastewater Master Plan (Final), Volume 1 – Terms of Reference and Summary Report, Project No.: 1594/01 Date: September 2012

Brazier, Anna (2015). Climate Change in Zimbabwe: facts for planners and decision makers. Harare: Konrad-Adenauer-Stiftung.

British Broadcasting Corporation (2012). Synchronised toilet flush held in Zimbabwe's Bulawayo. Available at http://www.bbc.co.uk/news/world-africa-19704766.

Brown, Donald, and others (2012). Climate change impacts, vulnerability and adaptation in Zimbabwe. Climate Change Working Paper, No. 3. London, UK: International Institute for Environment and Development.

Bulawayo Goetz Climate & Temperature. Avilable at http://www.bulawayo-goetz.climatemps.com/

Callow, Roger, and Alan MacDonald (2009). What will climate change mean for groundwater supply in Africa. Background Note. London: Overseas Development Institute.

Chivhenge, Emmerson and Mabaso, Aaron and Museva, Taona and Zingi, Godwin Kudakwashe and Manatsa, Proceed, (2022) Zimbabwe's Roadmap for Decarbonization and Resilience: An Evaluation of Policy (In) Consistency. Available at https://ssrn.com/abstract=4029469 or http://dx.doi.org/10.2139/ssrn.4029469

Crush, Jonathan., and Daniel Tevera, eds. (2010). Zimbabwe's exodus: Crisis, migration, survival. African Books Collective, SAMP, Cape Town and IDRC, Ottawa.

Damien Boulard, Pohl, B., Crétat, J., Vigaud, N., and Pham-Xuan, T., "Downscaling large-scale climate variability using a regional climate model: the case of ENSO over Southern Africa". Climate Dynamics, vol. 40, No. 5 (2013), pp.1141–1168.

David I. Leib and Thomas C. Stiles. "Yield Estimates for Surface-water Sources". Kansas Geological Survey, (1998), pp.159–170.

Davis, Mackenzie. L. Water and wastewater engineering: design principles and practice. McGraw-Hill Education, 2020.

Davis, R. and Hirji, R. (2014). Climate Change and Water Resources Planning, Development and Management in Zimbabwe - An Issues Paper, Richard Davis and Rafik Hirji, Washington, D.C.: World Bank, October 2014.

Davison Muchadenyika, Seeking urban transformation: alternative urban futures in Zimbabwe. Weaver Press, (2020).

Dodman, D and Mitlin, D. "The national and local politics of climate change adaptation in Zimbabwe". Climate and Development, vol. 7, No. 3 (2015), pp.223–234.

Dosio A and Panitz H-J., "Climate change projections for CORDEX-Africa with COSMO-CLM regional climate model and differences with the driving global climate models", Climate Dynamics vol. 46, (2016) pp 1599–1625.

Dube, Thulane., Saziso Sibanda., and Phibion Chiwara, "Adapting peri-urban agriculture to climate change in Bulawayo, Zimbabwe: A qualitative assessment", Cogent Social Sciences, vol. 7, No. 1 (2021), 1944486.

Evans, Henri-Count. (2015). Climate-change awareness and online media in Zimbabwe: opportunities lost. Knowledge for a Sustainable World: a Southern African-Nordic Contribution. Illustrated, reprint edn. African Minds and the Southern African-Nordic Centre, 163.

Fitchett, Jennifer, "Recent emergence of CAT5 tropical cyclones in the South Indian Ocean". South African Journal of Science, Vol. 114, No.11-12 (2018), pp.1–6.

Girardin, B. (2019). Does water have a cost? If so, which one? Seven theses. Blue ethics: Ethical perspectives on sustainable, fair water resources use and management/Ed. B. Girardin, E. Fiechter-Widemann.–Geneva: Globethics. net, pp.87–91.

Grafakos, S., Trigg, K., Landauer, M., Chelleri, L., and Dhakal, S. (2019). Analytical framework to evaluate the level of integration of climate adaptation and mitigation in cities. Climatic change, vol. 154, No. 1, pp.87–106.

Gwaze, P., Dahlin, T., Owen, R., Gwavava, O., and Danielsen, J. (2000). Geophysical investigations of the Karoo Aquifer at Nyamandhlovu, Zimbabwe. In Proceedings for the EEGS-ES 2000 Annual Meeting.

Hadebe, Methembe, H. (2015). Dry city: a history of water problems in Bulawayo, 1980–2014.

Hamilton M and Ndubiwa M. 1994. An attractive well designed city. In Hamilton M and Ndubiwa M (Eds), Bulawayo: A century of development, 8. Harare, Argosy Press.

Hoell, Andrew, and others, "The Modulation of Daily Southern Africa Precipitation by El Niño–Southern Oscillation across the Summertime Wet Season". Journal of Climate, vol. 34, No. 3 (2021), pp.1115–1134.

Kabell, T.C. (1974). The philosophy of reservoir yield and operational system from the maximum utilization of water resources. Department of Water Development, Harare, Zimbabwe.

Kahsay Zeraebruk, Alfred O. Mayabi and John M. Gathenya, "Assessment of Water Resources and Analysis of Safe Yield and Reliability of Surface Water Reservoirs of Asmara Water Supply System", Environment and Natural Resources Research, Vol. 7, No. 45. (2017).

Karimakwenda, T. (2012). Zimbabwe: Loan Scheme for Marginalized Areas Ignores Bulawayo. Available at http://allafrica.com/stories/201204051396.html. Retrieved on 4 April 2022.

Keener, Sarah., Luengo, M., and Banerjee, S. G. Provision of water to the poor in Africa: Experience with water standposts and the informal water sector. World Bank Policy Research Working Paper, No. 5387. Washington, D.C.: World Bank, 2010.

Killian Munzwa and Jonga Wellington, "Urban development in Zimbabwe: A human settlement perspective". Theoretical and Empirical Researches in Urban Management, vol 5, No. 5, (2010), pp. 120–146. https://www.jstor.org/stable/10.2307/24861509

Kileshye Onema, Rockstrom, J., Mazvimavi, D., Love, D., Mul, M., van Rooyen, A., et al. (n.d.). Influence of Human Activities on the Hydrology of the Insiza River, Limpopo Basin, Zimbabwe - Implications for Catchment Planning. Lubumbashi.

Justin Baker, (2012). "Water supply challenges in Bulawayo, Zimbabwe". GIS in water resources. Available at www. ce. utexas. edu/prof/maidment/giswr2012/TermPaper/Baker.pdf. Accessed in August 2021.

Makiwa, H. (2007). Government withholds water to Bulawayo. Retrieved from http://www.swradioafrica.com/news200907/byowater200907.htm or https://allafrica.com/stories/200709201100.html

Masocha, M., and others (2017). Remote sensing of surface water quality in relation to catchment condition in Zimbabwe. Physics and Chemistry of the Earth, Parts A/B/C, 100, pp. 13–18.

Matamanda, Abraham, R., Vera Nel, and Innocent Chirisa (2021). Introduction to the Urban Geography Scape of Zimbabwe. In Urban Geography in Postcolonial Zimbabwe, pp. 1–15). Springer, Cham.

Maúre, G., Pinto, I., Ndebele-Murisa, M., Muthige, M., Lennard, C., Nikulin, G., ... and Meque, A. (2018). "The Southern African climate under 1.5 C and 2 C of global warming as simulated by CORDEX regional climate models". Environmental Research Letters, vol. 13, No. 6, 065002.

Mavume, A.F., Rydberg, L., Rouault, M. and Lutjeharms, J.R., "Climatology and landfall of tropical cyclones in the south-west Indian Ocean". Western Indian Ocean Journal of Marine Science, vol. 8, No. 1, (2009).

Mazvimavi D (2010) "Investigating changes over time of annual rainfall in Zimbabwe". Hydrol Earth Syst Sci 14:2671–2679. Available at https://doi.org/10.5194/hess-14-2671-2010.

Moalafhi, Ditiro B., Ashish Sharma and Jason Evans. (2017). "Reconstructing hydro-climatological data using dynamical downscaling of reanalysis products in data-sparse regions–Application to the Limpopo catchment in southern Africa", Journal of Hydrology: Regional Studies, vol. 12, pp. 378–395.

Moyo, B., Madamombe, E., Love, D., and WaterNet, P. O. (2005, November). "A model for reservoir yield under climate change scenarios for the water-stressed City of Bulawayo, Zimbabwe". In Abstract Volume, 6th WaterNet/WARFSA/GWP-SA Symposium, Swaziland (p. 38).

Muchaparara Musemwa, "A tale of two cities: the evolution of the City of Bulawayo and Makokoba Township under conditions of water scarcity, 1894–1953". South African Historical Journal, vol. 55, No. 1, (2006a), pp.186–209.

________ "Disciplining a 'dissident'city: Hydropolitics in the city of Bulawayo, Matabeleland, Zimbabwe, 1980–1994". Journal of Southern African Studies, vol. 32, No. 2, (2006b), pp. 239–54.

Musemwa, M. (2003). (location Minneapolis, Minnesota, University of Minnesota Press, 2003).

Muthige M.S, J. Malherbe, F.A. Englebrecht, S. Grab, A. Beraki, T.R. Maisha, and J. Van der "Projected changes in tropical cyclones over the South West Indian Ocean under different extents of global warming", Environmental Research Letters, vol. 13, No. 6, (2018), p.065019.

National Research Council. Water reuse: potential for expanding the nation's water supply through reuse of municipal wastewater. Washington, D.C.: National Academies Press, 2012.

New Zimbabwe. China funds $1,2bn Zambezi Water Project. New Zimbabwe, 12 July 2012. Retrieved from New Zimbabwe: http://www.newzimbabwe.com/news-8476-China+funds+$1,2bn+Zambezi+Water+Project/news.aspx

Ngwenya, Bigboy, and others, "Emerging heat-related climate change influences; a public health challenge to health care practitioners and policy makers: insight from Bulawayo, Zimbabwe". International Journal of Disaster Risk Reduction, vol. 27 (2018), pp. 596–601.

Nicholas P. Simpson, Kayleen J. Simpson, Clifford D. Shearing and Liza R. Cirolia, "Municipal finance and resilience lessons for urban infrastructure management: a case study from the Cape Town drought". International Journal of Urban Sustainable Development, vol. 11, No. 3, (2019) pp. 257–276.

Noel Mkandla, Pieter Van der Zaag and Peter Sibanda. (2005). "Bulawayo water supplies: Sustainable alternatives for the next decade". Physics and Chemistry of the Earth, (2005), vol. 30, No. 11–16, (2005), p. 938.

NORPLAN A.S. (2001). Bulawayo Water Conservation and Sector Services Upgrading Project, Final Report, vol. 1, Bulawayo, Zimbabwe

Ouweneel, B., Winter, K., and Carden, K. "How different Cape Town residential suburbs helped avert Day Zero". H2Open Journal, vol. 3, No. 1 (2020), pp.118–134.

Quentin R. Grafton, Chu, L and Wyrwoll, P. "The paradox of water pricing: dichotomies, dilemmas, and decisions". Oxford Review of Economic Policy, vol. 36, No.1 (2020), 86–107.

Rusinga, Freeternity., and A.E. Taigbenu, "Groundwater resource evaluation of urban Bulawayo" aquifer", Water SA, vol. 31, No. 1 (2005), pp. 23–34.

Scarnecchia, T. (2011). Bulawayo Burning: The Social History of a Southern African City, 1893–1960.

Schmidt, Elizabeth. "Negotiated spaces and contested terrain: Men, women, and the law in colonial Zimbabwe, 1890–1939". Journal of Southern African Studies, Vol. 16, No. 4 (1990), pp. 622–648.

Sethi Sibanda, Grab, S. W and Ahmed, F., "An evaluation of the CORDEX regional climate models in simulating future rainfall and extreme events over Mzingwane catchment, Zimbabwe". Theoretical and Applied Climatology, vol. 140, No. 1, (2020), pp. 91–100.

________ "Long-term rainfall characteristics in the Mzingwane catchment of south-western Zimbabwe". Theoretical and Applied Climatology, vol. 139, No. 3, (2020), pp. 935–948.

Shakespear Mudombi, Godwell Nhamo and Mammo Muchie, "Socioeconomic determinants of climate change awareness among communal farmers in two districts of Zimbabwe". Africa Insight, vol. 44, No. 2 (2014), pp.1–15.

Shepherd Muchuru, Botai JO, Botai CM, Landman WA, Adeola AM, "Variability of rainfall over Lake Kariba catchment area in the Zambezi river basin, Zimbabwe". Theoretical and Applied Climatology 124: (2016), pp. 325–338. Available at https://doi.org/10.1007/s00704-015-1422-1 or https://link.springer.com/article/10.1007/s00704-015-1422-1

Sherman Mutengu, Zvikomborero Hoko and Fungai Makoni, "An assessment of the public health hazard potential of wastewater reuse for crop production. A case of Bulawayo city, Zimbabwe", Physics and Chemistry of the Earth, vol. 32, (2007), pp. 1195–1203.

Sihlanganiso Khumalo, (2013). "Water crisis in cities: an investigation into the contribution of water demand management towards mitigating the scarcity of potable water in the city of Bulawayo", PhD dissertation, University of South Africa, 2013.

Sibanda, Amaon, "A nation in pain: why the HIV/AIDS epidemic is out of control in Zimbabwe. International Journal of Health Services, vol. 30, No. 4 (2000), pp. 717–738.

Sibanda, K. (2018). The Politics of Water Crisis in the City of Bulawayo. School of Graduate Studies, University of Botswana E-mail: anderson@ mopipi. ub. bw Telephone:(267) 355 2391/2839, 196.

Sibanda T, "Groundwater recharge estimation and modelling of the Nyamandhlovu aquifer, Mid Zambezi Basin, Zimbabwe", MSc thesis, UNESCO-IHE Institute for Water Education, Delft, 2006.

Taonameso, S., Mudau, L. S., Traoré, A. N., and Potgieter, N., "Urban water conundrums in Zimbabwe–the role of water policy and its implementation gaps". Water Supply, vol. 22, No. 3, (2022), pp. 3526–3539.

Terence Ranger, "City versus state in Zimbabwe: colonial antecedents of the current crisis". Journal of Eastern African Studies, vol. 1, No. 2 (2007), pp. 161–192.

________ 2010. Bulawayo Burning. The Social History of a Southern African City 1893–1960. Suffolk, UK: James Currey. Available at https://www.jstor.org/stable/10.7722/j.ctt1bh4992

________ (2010). Bulawayo Burning: The Social History of a Southern African City, 1893–1960. Boydell and Brewer.

The Economist. (2010). Growth areas: The urbanization of Africa. Retrieved from The Economist: http://www.economist.com/blogs/dailychart/2010/12/urbanization_africa, 4 April 2004.

Tingju Zhu and Claudia Ringler, "Climate change implications for Water resources in the Limpopo Basin", IFPRI discussion paper, No. 00961 (Washington, D.C., International Food Policy Research Institute, 2010)

________ "Climate change impacts on water availability and use in the Limpopo Basin", Water vol. 4, No.1, (2012), pp. 63–84.

Tom Tom and Emmanual Munemo, "Republic of Zimbabwe national water policy: a desk review of the gaps between the policy and its implementation". International Journal of Public Policy and Administration Research, vol. 2, No. 3, (2015), pp. 60–72.

Treda Mukuhlani and Mandlenkosi Nyamupingidza, "Water scarcity in communities, coping strategies and mitigation measures: The case of Bulawayo". Journal of Sustainable Development, vol. 7, No. 1, (2014), p. 144.

Unganai, Leonard, S., "Vulnerability and adaptation of African ecosystems to global climate change", Climate Research, vol 6, No.2 (1996), pp. 137–145.

________ "Historic and future climatic change in Zimbabwe. Climate research", vol. 6, No. 2, (2021), pp. 137–145.

United Nations. (n.d.). Millennium Development Goals. Accessed on------- Available at [http://www.un.org/millenniumgoals/environ.shtml](http://www.un.org/millenniumgoals/environ.shtml)

United Nations Economic Commission for Africa. (n.d.). Africa Water Vision 2025. UNECA

Velasco, Marc., and others, "Resilience to cope with climate change in Urban Areas—A multisectorial approach focusing on water—The RESCCUE Project". Water, vol. 10, No. 10 (2018), p.1356.

VEI (2019) Short-Term Mission Report, Climate resistant water supply program 2050 for Harare and Bulawayo, WaterWorX Program Zimbabwe, Harare, Zimbabwe.

VisionRI (2019) Preparation Of A National Water Resources Master Plan, Interim Report – 5 (Draft), January 2019, Haryana-131001, India

Washington R. Nyabeze, "Calibrating a distributed model to estimate run-off for ungauged catchments in Zimbabwe". Physics and Chemistry of the Earth, (2005), pp. 625–633.

World Bank Group Climate Change Knowledge Portal (CCKP, 2021). Climate Data: Historical. Avilable at https://climateknowledgeportal.worldbank.org/country/zimbabwe (Accessed August 2021)

________ (2021). Climate Risk Country Profile: Zimbabwe, © 2021 by the World Bank Group, 1818 H Street NW, Washington, D.C., USA 20433

ZAMCOM, SADC, SARDC. 2015. Zambezi Environment Outlook 2015. ZAMCOM, SADC, SARDC. Harare, Gaborone

Zimbabwe, Ministry of Lands, Agriculture, Water, Climate and Rural Resettlement Climate Change Management Department, National Adaptation Plan Roadmap for Zimbabwe. Harare, 2019.

Zimbabwe, Mitchell, T.B. (1989). Ministry of Rural Resources and Water Development. "Notes on Programme Yield 98". Internal circular.

Zimbabwe, Ministry of Water, Environment and Climate. Zimbabwe's Third National Communication to the United Nations Framework Convention on Climate Change. Harare, 2016. Available at http://www.un-gsp.org/sites/default/files/documents/zwenc3.pdf (Accessed: December 2021).

Zimbabwe, (1924). Official Year Book of the Colony of Southern Rhodesia


## CHAPTER 3


Andreas Lindhe, Lars Rosén, Per-Olof Johansson and Tommy Norberg, "Dynamic Water Balance Modelling for Risk Assessment and Decision Support on MAR Potential in Botswana", Water, vol.12, No. 721, (2020). Available at doi:10.3390/w12030721

Arabang T. Kadibadiba, "A city in a water crisis: the responses of the people of Gaborone". Master

of Applied Science thesis, Lincoln University, 2017.

Batisani, Nnyaladzi and Yarnal, Brent (2010). Rainfall variability and trends in semi-arid Botswana: implications for climate change adaptation policy. Applied Geography, vol. 30. No. 4, pp 483 –489.

Botswana, Department of Surveys and Mapping, Botswana National Atlas. Gaborone, 2000.

_______Department of Water Affairs, Botswana National Water Master Plan Review. Gaborone, 2006.

_______ Department of Water Affairs, Botswana Integrated Water Resources Management & Water Efficiency Plan, vol. 1. Gaborone, 2013.

________ Department of Water Affairs, Botswana IWRM-WEP Main Report (2013). Gaborone, 2013.

________ Ministry of Lands and Housing, Botswana Habitat III Report. Gaborone, 2014.

________ Ministry of Local Government, Lands and Housing, Department of Town and Regional Planning, Urban Development Standards. Gaborone, 1992.

________, Ministry of Land Management, Water and Sanitation Services. National Water Master Plan Update based on Smart Water Management. Gaborone, 2018.

________, Ministry of Land Management, Water and Sanitation Services National Spatial Plan 2036. Gaborone, 2019.

________ Statistics Botswana, Botswana Environment Statistics 2012. Gaborone, 2012.

________ Statistics Botswana, Botswana Environment Statistics Water Digest 2018. Gaborone, 2018.

________ Statistics Botswana, Cities/Towns and Villages Projections 2020. Gaborone, 2020.

________ Statistics Botswana, Selected Statistical Indicators 1966–2016. Gaborone, 2016.

Denis Nono, Phillimon T. Odirile, Innocent Basupi, and Bhagabat P. Parida, "Assessment of Probable causes of chlorine decay in water distribution systems of Gaborone City, Botswana". Water SA, vol. 45, No. 2, (2019) (Published ISI Indexed, IF 1.077).

Food and Agriculture Organization of the United Nations. (2012). Agriculture and Food Security Policy Brief Reflecting on the Challenges of Attaining a Green Economy for Botswana. Botswana Agriculture Sector Policy Brief, pp. 1–7.

Ganesan C.T., (1998), Wastewater Management of Buildings in Botswana. CIB-W62 Water Supply and Drainage Symposium, 21–23 September. Rotterdam.

Gould J. E. and B. Jay (1993), An overview of catchment systems in Botswana. Proceedings of the Rainwater Catchment Systems Application and Technology Workshop. Gaborone, 1–3 March 1993.

Jimmy Byakatonda, B.P. Parida, Piet Kenabatho and D.B. , "Prediction of onset and cessation of austral summer rainfall and dry spell frequency analysis in semiarid Botswana", Theoretical and Applied Climatology, vol. 135, No. 1–2, (2018), pp. 101–117. Available at https://doi.org/10.1007/s00704-017-2358-4.

Kadibadiba, T., Roberts, L., Duncan, R., 2018. Living in a city without water: a social practice theory analysis of resource disruption in Gaborone, Botswana. Global Environmental Change, vol. 53, pp. 273–285. Available at https://doi.org/10.1016/J.GLOENVCHA.2018.10.005.

Kalabamu, Faustin and Morolong, S., (2004). Informal land delivery processes and access to land for the poor in Greater Gaborone. Working paper, No. 3. University of Birmingham

Kenabatho, P.K. and Parida, B.P (2005). "Evaporation losses as a major factor in determining allowable releases from water supply reservoirs: The case of Botswana's major reservoirs, River Basin Management III, 72", WIT Transactions on Ecology and the Environment, pp. 631–638.

Ker Rault, P.A., Jeffrey, P., Bouzit, M. (2004). Deliverable 19: Collated report on Water Vision Workshop for 2015: Amman Zarqa Basin Kingdom of Jordan; Chekka bay, Lebanon; Tartous Governorate, Syria; Gökova Basin, Turkey. Mediate EC-funded project no PL 509112.

Khupe SJN (1996). "Water, supply, sewage and waste management for Gaborone, Botswana". Ambio, vol. 25, No. 2, (1996), pp. 134–145.

Koundouri P., Ker Rault P., Pergamalis V., Skianis V., Souliotis I. (2016). Development of an integrated methodology for the sustainable environmental and socio-economic management of river ecosystems. Science of the Total Environment vol. 540, pp. 90–-100

Lindhe et al (2020)

Maúre, G., Pinto, I., Ndebele-Murisa, M., Muthige, M., Lennard, C., Nikulin, G., Dosio, A., and Meque, A. (2018). The Southern African climate under 1.5 °C and 2 °C of global warming as simulated by CORDEX regional climate models. Environmental Research Letters, vol. 13, No. 6, 065002, (2018).

Moalafhi, Ditiro B. "Effects of Urbanization on the flow regime of Notwane", MPhil Thesis, University of Botswana, 2004.

Moalafhi, Ditiro B. (2008b). Water Resources of Botswana-An overview, Proc. of the IASTED Intl. Conf. on Science and Technology Innovation for Sustainable Development, 8–10 September 2008. Gaborone, Botswana.

Moalafhi, Ditiro B., Tsheko R., Atlhopheng J.R., Odirile P.T., Masike S., "Implications of climate change on water resources of Botswana", Advance Journal of Physical Sciences, vol. 1, No. 2, (2012), pp. 4–13.

Moalafhi, Ditiro B., Ashish Sharma, Jason P. Evans, "Reconstructing hydro-climatological data using dynamical downscaling of reanalysis products in data-sparse regions – Application to the Limpopo catchment in southern Africa", Journal of Hydrology: Regional Studies, vol. 12, (2017) pp. 378–395. Available at doi: 10.1016/j.ejrh.2017.07.001

Nkemelang Tiro, New Mark and Modathir Zaroug, "Temperature and precipitation extremes under current, 1.5 °C and 2.0 °C global warming above pre-industrial levels over Botswana, and implications for climate change vulnerability", Environmental Research Letters, vol. 13, 065016, (2018)

Nono et al (2019)

Nnyaladzi, Batisani, and Brent Yarnal, B (2010). "Rainfall variability and trends in semi-arid Botswana: implications for climate change adaptation policy", Applied Geography, vol. 30, No. 4, (2010), pp. 483–489.

Nyoni, Thabani, (2019). What will be Botswana's population in 2050? Evidence from the Box-Jenkins approach. MPRA Paper No. 93977. Available at https://mpra.ub.uni-muenchen.de/93977/

Parida, Bhagabat P., and Ditiro B. Moalafhi, "Regional rainfall frequency analysis for Botswana using L-Moments and radial basis function network". Physics and Chemistry of the Earth, vol. 33, (2008a), pp. 614–620.

Phoebe Koundouri P., and others, "Development of an integrated methodology for the sustainable environmental and socioeconomic management of river ecosystems", Science of the Total Environment, vol. 540, (2016), pp. 90–100.

Ranganai, Rubeni, T., Gotlop-Bogatsu, Y., Maphanyane, J. and Tladi, B. (2001). Hydrochemical and Geophysical Evaluation of Groundwater Pollution in the Ramotswa Wellfield, SE Botswana. BIE2001 Technical Papers, 193–200.

Silitshena, R.M.K., "Urbanization in Botswana", Nordic Geographical Journal, vol. 38, (19840, pp. 109–128.

Swart, H. S., van Rooyen, P. G., Mwaka, B. B., & Ntuli, C., (2007). Operating Rules for Dams with High Evaporation Losses. Pretoria, South Africa: WRP Consulting Engineers and the Department of Water Affairs and Forestry, Directorate of Water Resource Planning Systems, South Africa

Thomas, David G.S., and Paul A. Shaw. (1991). The Kalahari Environment. Cambridge University Press.

Tiro Nkemelang, Mark New and Modathir Zaroug, "Temperature and precipitation extremes under current, 1.5 °C and 2.0 °C global warming above pre-industrial levels over Botswana, and implications for climate change vulnerability", Environmental Research Letters, vol. 13, 065016, (2018)

Tyson, P.D. and Crimp, S.J., (2000). The climate of the Kalahari transect. Towards sustainable management in the Kalahari region – some essential background and critical issues. Directorate of Research and Development, University of Botswana. Gaborone, Botswana, 2000.

United Nations Human Settlements Programme. (2016) Urbanization and Development: Emerging Futures. World Cities Report 2016, United Nations Centre for Human Settlements, Nairobi

van Nostrand, John. Old Naledi: The Village Becomes a Town. Toronto, James Lorrimer & Company, (1982).

Water Policy Brief Reflecting on the Challenges of Attaining a Green Economy for Botswana.

Botswana Water Sector Policy Brief 2012.

World Bank (2014). Accounting for Water in Botswana. The Wealth Accounting and the Valuation of Ecosystem Services ( or WAVES) Botswana programme.

________ (2015). Botswana Poverty Assessment. Report No. 88473-BW.

________ (2017). Groundwater Monitoring Assessment Study Botswana. Final Report: Prepared by John L. Farr, Gaborone, Botswana.


## CHAPTER 4


Africa Development Bank Group (2015). Environmental and Social Management Framework: Lusaka Sanitation Project Report. ADB. Abidjan.________ (2017).

Ahlers, Rhodante, and others, "Informal Space in the Urban Waterscape: DIssagregation and Co-production of Water Service", Water Alternatives. vol. 7, No.1 (2014), 1–14.

Ashraf, N., Delfino, A. and Glaeser, E. (2018). Urban Density, Trust and the Growth of Small

Businesses in Lusaka, Zambia. Innovations for Poverty Action. Available at https://www.poverty-action.org/study/urban-density-trust-and-growth-small-businesses-lusaka-zambia

Beekam, H. (2016). Lusaka's Water Security Situation Analysis. Publication 1: Water Risks and Solutions Assessment. Lusaka Water Security Initiative (LuWSI). Lusaka.

Funded by UKAID, IWASP and GIZ.

Chisola, Moses N., and Michal Kuráž, M (2016). "Patterns and Implications of Hydrologic Regime Change in Chongwe River, Zambia", Journal of Geography and Geology. vol 8, No 3. (2016)/

Chitonge, Horman (2012). Water Services Reforms in Zambia, Global Water Forum. Available at http://www.globalwaterforum.org/2012/01/30/water-services-reforms-in-zambia-2000-2010/

CSAG/FRACTAL (2018)

Davis-Reddy, C. L., ed. Climate Risk and Vulnerability: A handbook for Southern Africa. Council for Scientific and Industrial Research, Pretoria, South Africa, 2011. Available at: http://researchspace.csir.co.za/dspace/handle/10204/10066.

De Waele Jo., and others. "Urban waste landfill planning and karstic groundwater resources in developing countries: The example of Lusaka (Zambia)", Journal of African Earth Sciences. Vol. 39, (2004), pp. 501–-508.10.1016/j.jafrearsci.2004.07.014.

Drescher, A.W. (1997). Urban Agriculture In The Seasonal Tropics Of Central Southern Africa: A Case Study Of Lusaka, Zambia. City Farmer, Canada's Office of Urban Agriculture

Food and Agriculture Organization of the United Nations, City Region food system Programme: Lusaka Zambia, 2023. Available at: https://www.fao.org/in-action/food-for-cities-programme/pilotcities/lusaka/en/.

Foster, V. and Dominguez, C. (2010) Zambia's Infrastructure: A Continental Perspective, Africa Infrastructure Country Diagnostic.

Fröhlich, S. (2019). Africa's Fastest Growing Cities. Deutsche Welle Akademie. Available at https://p.dw.com/p/3NM4t

Grönwall, J.T., Mulenga, M. and McGranahan, G. (2010) Groundwater self supply and poor urban dwellers: A review with case studies of Bangalore and Lusaka.

International Institute for Environment and Development, London.

Karen, Max, Tobias Godau, and Peter Petulo. Review and Rehabilitation of the Lusaka

Groundwater Monitoring Network. Technical Note No. 1. Water Resources Management

Authority, Zambia & Federal Institute for Geosciences and Natural Resources, Germany. Lusaka, 2019.

Karen, Max, and others. Investigation of Groundwater Vulnerability and Contamination in Lusaka as Possible Factors in the 2017/18 Cholera Epidemic. Technical Report No. 1. Water Resources Management Authority, Zambia & Federal Institute for Geosciences and Natural Resources, Germany. Lusaka, 2019.

Kay, George. A Social Geography of Zambia. London: University of London Press, 1967.

Libanda, Brigadier., and Chilekana Ngonga. (2018). "Projection of frequency and intensity of extreme precipitation in Zambia: a CMIP5 study", Climate Research. Vol. 76, No. 59–72 (2018). Available at DOI:https://doi.org/10.3354/cr01528.

Lusaka City Council, Lusaka Situation Analysis. Lusaka, 2005.

Lusaka City Council and Environmental Council of Zambia, Lusaka City State of Environment Outlook Report. Lusaka, 2008.

Lusaka Times, Firm invests K300 million to build 60 dry toilets. Available at https://www.lusakatimes.com/2011/10/31/firm-invests-k300m-build-60-dry-toilets/. Accessed on 19 March 2023.

Lusaka Water and Sewerage Company. Lusaka Water and Sewerage Company Strategic Plan 2018–2022. Lusaka: New Horizon Printing Press, 2018.

Matamyo Simwanda., and Yuji Murayama, "Integrating Geospatial Techniques for Urban Land Use

Classification in the Developing Sub-Saharan African City of Lusaka, Zambia", ISPRS International Journal of Geo-Information, vol. 6, p.102, 2017. Available at doi:10.3390/ijgi6040102.

MCA 2011 Base line indicators

Meerow, Sara., and Sierra C. Woodruff, "Seven Principles of Strong Climate Change

Planning", Journal of the American Planning Association, vol. 86, No. 1 (2020), pp. 39–46. Available at DOI: 10.1080/01944363.2019.1652108.

Nchito, Wilma S., and others (2018). Understanding Interactions Between Urban Floods, Municipal

Solid Waste and Urban Planning in The Lusaka City-Region. Final Project Report for 2016 START Grants for Global Change Research in Africa.

Nkonkomalimba, Mpala., and Moses Mumba. Sustainability and Equity Review of CARE Zambia's Peri Urban Water and Sanitation Model. CARE International. Lusaka, 2014.

Nussbaumer, David., Ian Sutton, and Alison Parker, "Groundwater Data Management by Water Service Providers in Peri-Urban Areas of Lusaka", Water, vol. 8, No.4 (2016), pp.135–146. Available at https:doi.org /10.3390/w8040135

Pradeep P. Majumdar, "Implications of climate change for sustainable water resources management in India", Physics and Chemistry of the Earth, vol 33 (2008), pp. 345–358.

Sampson, R. So this was Lusaaka's the story of the capital of Zambia. Multimedia Publications, Lusaka, 2017.

Sladoje, (2018)

Suresh Kumar Rohilla, Mahreen Matto, Shivali

Jainer and Chhavi Sharda (2017). Water-Sensitive Urban Design and Planning: A Practitioner's Guide, Centre for Science and Environment. New Delhi.

Suresh Kumar Rohilla, Mahreen Matto, Shivali Jainer and Chhavi Sharda (2017). 0, Centre for Science and Environment. New Delhi. Available at: https://pdf.usaid.gov/pdf_docs/PNADO942.pdf. Accessed on 16 March 2022.

United State Agency for International Development (n.d) Zambia: Water and Sanitation Profile. USAID.

Vairavamoorthy, K., Gorantiwar, S. D. and Pathirana, A. "Managing urban water supplies in developing countries- Climate change and water scarcity scenarios", Physics and Chemistry of the Earth, Vol. 33, (2008), pp. 330–339.

Water and Sanitation for the urban Poor. Towards citywide sanitation in Lusaka: The next phase of non-sewered sanitation. Topi Brief, WSUP Lusaka. February 2018. Available at https://www.wsup.com/content/uploads/2018/04/02-2018-Towards-citywide-sanitation-in- Lusaka_online.pdf. Accessed on 20 March 2023.

Williams, J.G. (1984). The Peugeot Guide to Lusaka. Zambia Geographical Association Occasional Study No.12. Ndola: Mission Press.

Williams, J.G. (1986a), "The Early Years of the Township, in Williams J.G. (ed) Lusaka and Its Environs", Zambia Geographical Association Handbook Series No. 9, pp. 71–94.

Williams, J.G. (1986b) "The Physical Growth of Lusaka: Past and Projected", in Williams J.G. (ed)

Lusaka and Its Environs. Zambia Geographical Association Handbook Series No. 9: pp. 138–154.

Zambia, Comprehensive Urban Development Plan. Vol.1. Final Report. Japan International Cooperation Agency, Lusaka, 2009.

Integrated Water Resources Management and Water Efficiency Implementation Plan.

Volume. 1: Main Report (2007–2030). Lusaka, 2008.

Ministry of Energy and Water Development. National Water Policy. Lusaka, 1994.

Ministry of Finance, Project report (unpublished), 2013. Ministry of Finance. Strengthening Climate Resilience in the Kafue Basin Project.

Strategic Environmental and Social Assessment. Executive Summary. Africa Development Bank Group. Lusaka, 2013. Ministry of Local Government and Housing. Comprehensive Urban Development Plan, Volume I, Final Report. Japan International Co-operation Agency, Government of the Republic Zambia, Lusaka, 2009.

_________Ministry of Tourism and Natural Resources. Formulation of the National Adaptation Programme of Action on Climate Change. NAPA, Government of the Republic Zambia, Lusaka, 2007.

_________ Ministry of Tourism and Natural Resources. Climate change response strategy (NCCRS). Lusaka, 2010.

_________ Zambia Statistical Agency. 2010 Census of population and housing: Population and Demographic Projections 2011–2035. Lusaka, 2013._________ Ministry of Water and Energy Development. Water Supply Study Report. GAUFF Engineering. Lusaka, 2016.

_________ Ministry of Water Development, Sanitation and Environment. Integrated Water

Resources Management and Water Efficiency (IWRM/WE) Implementation Plan. Volume 1:

Main Report (2007 – 2030). Lusaka, 2008.

_________ National Water and Sanitation Council, Urban and Peri-urban Water Supply and

Sanitation Sector Report. Available at https://www.nwasco.org.zm/index.php/media-center/publications/urban-and-peri-urban-wss-sector reports?task=download.send&id=81&catid=12&m=0. Accessed on 20 March 2022.

Zeravica, K., ed (2016). Water in the Zambian Economy. WWF-World Wide Fund for Nature, Printech Limited, Lusaka.

## CHAPTER 5

Archer, Emma, and others. Seasonal prediction and regional climate projections for Southern

Africa. Windhoek: Klaus Hess Publishers. 2018.

Biggs, D., and Williams, R. (2001). A case study of integrated water resource management in

Windhoek, Namibia. In Frontiers in urban water management: Deadlock or hope, pp. 10–18.

Bloom, David E. (2007). Governing global health. Finance and Development, vol. 44, No. 4 (December).

Bruce, Hugh S., and Gysbertus J. Burger (2019). Historical assessment of water resource management and development in Windhoek and the Central Area of Namibia. Presented at the Water Storage and Hydropower Development for Africa Conference. Windhoek, 2–4 April.

Cecilia Tortajada, and Pierre van Rensburg, (2020). Drink more recycled wastewater. Water.

Christelis, Greg, and Wilhelm Struckmeier, Groundwater in Namibia: An explanation to the hydrological map. John Meinert Printing. Windhoek: Department of Water Affairs, Windhoek (Namibia ), 2001.

City of Windhoek (2019). Water Management Plan.

City of Windhoek (2021). Notes (Unpublished).

Connor, Richard (2015). The United Nations world water development report 2015: Water for a Sustainable World, UN Water Report. vol. 1. UNESCO publishing.

Du Pisani, Petrus. L. (2004). Surviving in an arid land: Direct reclamation of potable water at Windhoek's Goreangab Reclamation Plant. Arid Lands Newsletter, 56.

_________ "Direct reclamation of potable water at Windhoek's Goreangab reclamation plant", Desalination, Vol. 188, No. 1 (2006), pp. 79–88.

Erastus Nghinomenwa (2020). Namibia's ghetto life: Half million live in shacks countrywide. The Namibian, 12 August. p. 1. Archived from the original on 21 April 2021. Retrieved 24 July 2021.

Frayne, Bruce, " Migration and the changing social economy of Windhoek, Namibia", Development Southern Africa, vol. 24, No. 1, (2007), pp. 91–108. Available at DOI: 10.1080/03768350601165918

http://www.meteona.com/

https://www.sei.org/featured/windhoek-climate-change-plan/; retrieved 10 August 2021.

Josef Lahnsteiner and G. Lempert (2007). Water management in Windhoek, Namibia

Lafforgue, Michel., and V. Lenouvel, "Closing the urban water loop: lessons from Singapore and Windhoek", Environmental Science: Water Research & Technology, vol. 1, No. 5 (2015), pp. 622–631.

Lahnsteiner, Josef., Pierre Van Rensburg., and J. Esterhuizen, "Direct potable reuse–a feasible water management option. Journal of Water Reuse and Desalination, vol. 8, No. 1 (2018), pp. 14–28.

Lewis Earl W., Chad Staddon, and Johannes Sirunda, "Urban water management challenges and achievements in Windhoek, Namibia", Water Practice and Technology, vol. 14, No. 3 (2019), pp.703–713.

Magnusson Therese S., and B. van der Merwe, "Context driven policy design in urban water management. A case study of Windhoek, Namibia", Urban Water Journal, vol. 2, No. 3, (2005), pp. 151–160.

Mapani, Benjamin S., and Ute Schreiber, "Management of city aquifers from anthropogenic Activities: Example of the Windhoek aquifer, Namibia", Physics and Chemistry of the Earth, Parts A/B/C, vol. 33, No. 8–13 (2008), 674–686.

Marelize Mostert, "Urban water supply and demand management: a case study of Windhoek, Namibia". Doctoral dissertation, Stellenbosch University, 2017.

Namibia, Ministry of Environment and Tourism, Climate change Vulnerability and Adaptation Assessment of Namibia. Desert Research Foundation of Namibia. Windhoek, 2008. Retrieved 17 September 2021. Available at http://www.landscapesnamibia.org/mudumu/sites/default/files/resources/Namibia%20Climate%20Change%20Vulnerability%20and%20Adaptation%20Assessment.pdf

Namibia, Namibia Meteorological Services, (2021).

Namibia, Namibia Water Corporation (2021). Notes (Unpublished).

Pazvakawambwa, Godfrey T., and A. Ogunmokun (2017). A time-series forecasting model for Windhoek Rainfall, Namibia.

Remmert, Deitrich (2017). Managing Windhoek's Water Crisis: short-term success vs long-term uncertainty, Democracy Report. Special Briefing Report No.18. Available at https://www.researchgate.net/profile/Dietrich-

Remmert/publication/343418247_Managing_Windhoek's_Water_Crisis_short-term_success_vs_long-term_uncertainty/links/5f294ae892851cd302d87c14/Managing-Windhoeks-Water-Crisis-short-term-success-vs-long-term-uncertainty.pdf , Retrieved 17 September 2021.

Savela, Nina, and others., "Rapid Urbanization and Infrastructure Pressure: Comparing the Sustainability Transition Potential of Water and Energy Regimes in Namibia", World, vol. 1, No. 2 (2020), pp. 49–66.

Selm T. Karuaihe, and Phillip R. Wandschneider, "Limited access to services for the urban poor in Windhoek, Namibia", Development Southern Africa, vol. 35, No. 4 (2018), pp. 466–479.

SLR. (2018). Sustainability Study of the Windhoek North Aquifer, Prepared for Namibia Breweries Limited by SLR Environmental Consulting, Namibia.

Stockholm Environment Institute (SEI) (2019).

Tuyeimo Haidula (2015). City to fine residents for not saving water. The Namibian, 10 June. Available at https://www.namibian.com.na/137916/archive-read/City-to-fine-residents-for-not-saving-water-IN-A

Uhlendahl, Thomas., and others (2010). Water consumption at household level in Windhoek, Namibia. Final project report, Albert Ludwigs University. Available at: https://freidok. uni-freiburg. de/dnb/download/7937 (Accessed 24 September 2021).

United Nations Framework Convention on Climate Change (2015). Paris Agreement: FCCC/CP/2015/L.9/Rev.1. Available at https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf Retrieved 17 September 2021.

Van Rensburg, Pierre, "Overcoming global water reuse barriers: the Windhoek experience", International Journal of Water Resources Development, vol. 32, No. 4 (2016), 622–636.

Van Rensburg Pierre., and Cecilia Tortajada (2021). An evaluation of the 2015–2017 drought in Windhoek to serve as guidance for future sustainable urban water supply in Southern African cities. Frontiers in Climate.

Van der Merwe, Ben. (1999). Case study on water demand management in Windhoek. IUCN Water Demand Management Country Study–Namibia, pp. 10–39.

Van der Walt, Charl (2003). Multiple Barriers Ensure Safe Potable Water from Reclaimed Sewage – Windhoek, Namibia

Wallmann Lina., and others, "Fate and persistence of antibiotic-resistant bacteria and genes through a multi-barrier treatment facility for direct potable reuse", Journal of Water Reuse and Desalination. Vol. 11, No. 3 (2021), pp. 373–390.

Weber, Ben, and J. Mendelsohn, (2017). Informal settlements in Namibia: their nature and growth: exploring ways to make Namibian urban development more socially just and inclusive. Development Workshop Namibia.

Windhoek Goreangab Operating Company (Wingoc) (2021). Notes. Unpublished.

Winsemius, Hessel., and others "Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts", Environment and Development Economics, vol. 23, No. 3 (2018) 328–348.

World Bank (2002). Upgrading of low-income settlements, country assessment report, Namibia.________. (2021). Available at https://climateknowledgeportal.worldbank.org/country/namibia/climate-sector-water . Retrieved 20 July 2021.

Zhang, Jinhui., R. Murray., and G. Tredoux (2004). Regional fractured aquifer modelling using telescopic mesh refinement (TMR) method. In Proceedings of the 2004 Water Institute of Southern Africa (WISA) Biennial Conference,Vol. 2, pp. 351–359).


## CHAPTER 7


Adams, Ellis, Sambu D, and Sarah L. Smiley, "Urban water supply in Sub-Saharan Africa: historical and emerging policies and institutional arrangements", International Journal of Water Resources Development, vol. 35, No. 2 (2019), pp. 240–263.

Akram, Fatima., and others "A review on stormwater harvesting and reuse", International Journal of Environmental, Earth Science and Engineering, vol. 8, No. 3 (2014), pp. 178–187.

Arnold, R. G., Sáez, A. E., Snyder, S., Maeng, S. K., Lee, C., Woods, G. J., ... and Choi, H., "Direct potable reuse of reclaimed wastewater: It is time for a rational discussion", Reviews on Environmental Health, vol. 27, No. 4, (2012), pp. 197–206.

Bahri, Akissa (2012). Integrated urban water management. TEC Background Papers, vol. 16, 1–89.

Bahri, Akiça., and Takashi Asano (2011). Global challenges to wastewater reclamation and reuse. On the Water Front, 64.

Brikké, François., and Vairavamoorthy, K., “Managing change to implement integrated urban water management in African cities”, Aquatic Procedia, vol. 6, (2016), pp. 3–14.

Chapin III, F. Stuart., Kofinas, G. P., and Folke, C., eds. (2009). Principles of Ecosystem Stewardship: resilience-based natural resource management in a changing world. Springer Science and Business Media.

Chigudu, S., The politics of cholera, crisis and citizenship in urban Zimbabwe: People were dying like flies”. African Affairs, vol. 118, No. 472, (2019), pp. 413–434.

Chikeya, T. S. (2018). “Causes of Cholera Outbreak in Zimbabwe: Case study of Chegutu, January 2018”, PhD dissertation, Bindura University of Science Education, 2018.

Cleland, David. I. (2007). Project Management: Strategic Design and Implementation. McGraw-Hill Education.

Danilenko, Alexander., and others (2014). The IBNET Water Supply and Sanitation Blue Book 2014. Washington, D.C.: World Bank. Available at doi:10.1596/978-1-4648-0276-8.

Davis, Jennifer, “Private-sector participation in the water and sanitation sector”, Annual Review of Environment and Resources, vol. 30, (2005), pp. 145–183.

Davison, Annette, Howard G, Stevens M., and others (2005). Water safety plans: managing drinking-water quality from catchment to consumer. Geneva, World Health Organization, (WHO/SDE/WSH/05.06).

Davison, Annette, Deere, D., Stevens, M., and others (2009). Water Safety Plan Manual: step-by-step risk management for drinking-water suppliers.

Day, Jake. K., and Ashok K. Sharma,“Stormwater harvesting infrastructure systems design for urban park irrigation: Brimbank Park, Melbourne case study. Journal of Water Supply: Research and Technology-Aqua, vol. 69, No. 8 (2020), pp. 844–857.

Diduck, Alan., 2010. The Learning Dimension of Adaptive Capacity: Untangling the Multi-level Connections. In Adaptive Capacity and Environmental Governance, D. Armitage and R. Plummer, eds. Springer-Verlag, Heidelberg, pp. 199–222.

Dirwai, Tinashi. L., and others, “Water resource management: IWRM strategies for improved water management. A systematic review of case studies of East, West and Southern Africa”, Plos One, vol. 16, No. 5, (2021) e0236903.

Dithebe, Khotso., Clinton Aigbavboa., and Didi W. Thwala, (2019). An Appraisal of Water Infrastructure Projects’ Financing Challenges in South Africa. In 10th Nordic Conference on Construction Economics and Organization. Emerald Publishing Limited.

Du Pisani, Petrus., and J.G. Menge, “Direct potable reclamation in Windhoek: a critical review of the design philosophy of new Goreangab drinking water reclamation plant”, Water Science and Technology: Water Supply, vol. 13, No. 2 (2030), pp. 214–226.

Echegaray, Fabian, “What POST-COVID-19 lifestyles may look like? Identifying scenarios and their implications for sustainability”, Sustainable Production and Consumption, vol. 27, (2021), pp. 567–574.

Ehlers, T. (2014). Understanding the challenges for infrastructure finance, Bank for International Settlements, Basel, Switzerland

Fatch, Joanna. J., Manzungu, E., and Collin Mabiza, “Problematising and conceptualising local participation in transboundary water resources management: The case of Limpopo river basin in Zimbabwe”, Physics and Chemistry of the Earth, Parts A/B/C, vol. 35, No. 13–14 (2010), pp. 838–847.

Fisher-Jeffes, Lloyd., and others, “Stormwater harvesting: Improving water security in South Africa’s urban areas”, South African Journal of Science, vol. 113, No. 1–2) (2017), pp. 1–4.

Flyvbjerg, Bent, “What you should know about megaprojects and why: An overview”, Project Management Journal, vol. 45, No. 2 (2014), pp. 6–19.

Frascari, Dario., and others,“Integrated technological and management solutions for wastewater treatment and efficient agricultural reuse in Egypt, Morocco, and Tunisia”, Integrated Environmental Assessment and Management, vol. 14, No. 4 (2018), pp.447–462.

Gasse, Françoise, and others, “Climatic patterns in equatorial and southern Africa from 30,000 to 10,000 years ago reconstructed from terrestrial and near-shore proxy data”, Quaternary Science Reviews, vol. 27, No. 25–26 (2008), pp. 2316–2340.

Heaney, James. P. (2000). Principles of integrated urban water management. Innovative urban wet-weather flow management systems, pp. 36–73.

Henderson, J. Vernon., Storeygard, Adam., and Uwe Deichmann. 50 Years of Urbanization in Africa: Examining the Role of Climate Change. Policy Research Working Paper, No. 6925. Washington, D.C.: World Bank, 2014.

Hoffmann, Sabine., and others “A research agenda for the future of urban water management: exploring the potential of non-grid, small-grid, and hybrid solutions”, Environmental Science and Technology, vol. 54, No. 9 (2020), pp. 5312–5322.

Huang, Yiping. “Understanding China’s Belt and Road initiative: motivation, framework and assessment”, China Economic Review, vol. 40, (2016), pp. 314–321.

Hulme, Mike., and others “African Climate Change: 1900–2100”, Climate Research, vol. 17, (2001), pp. 145–168. Available at DOI: 10.3354/cr017145

Hulsman, Petra., Hubert Savenije., and Markus Hrachowitz, “Satellite-based drought analysis in the Zambezi River Basin: Was the 2019 drought the most extreme in several decades as locally perceived?” Journal of Hydrology: Regional Studies, vol. 34, (2021), 100789.

International Water Association.

Kahinda, J. Mwenge., Akpofure E. Taigbenu., and R.J. Boroto, “Domestic rainwater harvesting as an adaptation measure to climate change in South Africa”, Physics and Chemistry of the Earth, Parts A/B/C, (2010) vol. 35. No. 13–14, pp. 742–751.

Kim, Yoon., and others “A perspective on climate-resilient development and national adaptation planning based on USAID’s experience”, Climate and Development, vol. 9, No. 2 (2017), pp. 141–151.

Kinkade-Levario, Heather. Design for Water: Rainwater Harvesting, Stormwater Catchment and Alternate Water Reuse. New Society Publishers, 2007.

Kiparsky, Michael., and others “The innovation deficit in urban water: the need for an integrated perspective on institutions, organizations, and technology”, Environmental engineering science, vol. 30, No. 8 (2013), pp. 395–408.

Kirshen, Paul., and others “Integrated urban water management applied to adaptation to climate change”, Urban Climate, vol. 24, (2018), pp. 247–263.

Lahnsteiner, Jonathan., Pierre Van Rensburg., and Jacques Esterhuizen, “Direct potable reuse–a feasible water management option”, Journal of Water Reuse and Desalination, 8(1), (2018), pp. 14–28.

Laitinen, Jyrki., and others "Water Supply and Sanitation in a Green Economy Society: The Case of Finland", Public Works Management and Policy, vol. 25, No. 1 (2020), pp. 33–50.

Lukes, Steven. Power: A Radical View. Second ed. New York: Palgrave Macmillan, 2005.

Lyu, Sidan., and others. "Wastewater reclamation and reuse in China: opportunities and challenges", Journal of Environmental Sciences, vol. 39, (2016), pp. 86–96.

Masi, Fabio., Rizzo, A., and Riccardo Bresciani, "Green architecture and water reuse: examples from different countries", Sustainable Sanitation Practice, vol. 23, (2015), pp. 4–10.

Matamanda, Abraham, R., "Battling the informal settlement challenge through sustainable city framework: experiences and lessons from Harare, Zimbabwe", Development Southern Africa, vol. 37, No. 2 (2020), pp. 217–231.

Mitchell, V. Grace, "Applying integrated urban water management concepts: a review of Australian experience", Environmental Management, vol. 37, No. 5 (2006), pp. 589–605.

Mtanda, Masfiri. M., Sakshi Gupta., and Deepak Khare (2021). Rainwater Harvesting System Planning for Tanzania. In Water Management and Water Governance, pp. 413–425. Springer, Cham.

Mukwada, Geoffrey., Manatsa, D., and Enock Makwara, Integrated Water Resources Management in Southern Africa Two Decades After the Dublin Conference: The Zimbabwean Experience. In Water Science and Sustainability, pp. 23–41. Springer, Cham, 2021.

National Oceanic and Atmospheric Administration (2020). National Centers for Environmental Information, State of the Climate: Global Climate Report for Annual 2019, published online January 2020. Available at: https://www.ncdc.noaa.gov/sotc/global/201913 (Accessed August 2021).

Namibia, Ministry of Environment and Tourism, Climate Change Vulnerability & Adaptation Assessment, Namibia. March 2008

Nhapi, I. (2015) Challenges for water supply and sanitation in developing countries: case studies from Zimbabwe.In Grafton, Q., Daniell, K.A., Nauges, C., Rinaudo, J.-D., Chan, N.W.W., eds, Understanding and Managing Urban Water in Transition. Springer Global Issues in Water Policy, vol. 15, pp. 91–119.

Ociepa, Ewa., Mrowiec, M., and Iwona Deska, "Analysis of water losses and assessment of initiatives aimed at their reduction in selected water supply systems", Water, vol. 11, No. 5 (2019), p.1037.

Parkinson, Jonathan N., Joel A. Goldenfum., and Carlos Tucci, eds. (2010). Integrated Urban Water Management: Humid Tropics: UNESCO-IHP, vol. 6. CRC Press.

Radcliffe, John. C. (2019). History of water sensitive urban design/low impact development adoption in Australia and internationally. In Approaches to Water Sensitive Urban Design, Woodhead Publishing, pp. 1–24.

Rakodi, Carole (2016). The Urban Challenge in Africa. In Managing Urban Futures, pp. 63–86). Routledge.

Richmond, Amy., Myers, I., and Hafisa Namuli, "Urban informality and vulnerability: A case study in Kampala, Uganda". Urban science, vol. 2, No. 1 (2018), p. 22.

Roccaro, Paolo. "Treatment processes for municipal wastewater reclamation: The challenges of emerging contaminants and direct potable reuse", Current Opinion in Environmental Science and Health, vol. 2, (2018), pp. 46–54.

Saja, Aslam. M., Sahid, S. M., and M. Sutharshanan (2021). Capacity-Building Strategy for Creating Disaster-and Climate-Risk-Sensitive Development Plans—A Case Study of Multi-Stakeholder Engagement in Sri Lanka. In Integrated Research on Disaster Risks, pp. 231–249. Springer, Cham.

Schreiner, Barbara, and Hannah Baleta, "Broadening the lens: a regional perspective on water, food and energy integration in SADC", Aquatic Procedia, vol. 5, (2015), pp. 90–103.

Sjöstedt, Martin, "The impact of secure land tenure on water access levels in sub-Saharan Africa: The case of Botswana and Zambia", Habitat International, vol. 35, No. 1 (2011), pp. 133–140.

Spalding-Fecher, Randall., Brian Joyce., and Harald Winkler, "Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: System-wide impacts and policy implications", Energy Policy, vol. 103, (2017), pp. 84–97.

Swatuk, Larry A. "Political challenges to implementing IWRM in Southern Africa", Physics and Chemistry of the Earth, Parts A/B/C, vol. 30, No. 11–16 (2005), pp. 872–880.

Tam, Vivian, W., Ki Kim., and Andrew Brohier, "Life-cycle analysis by using the alternative sustainable water innovations in residential dwellings", International Journal of Construction Management, vol. 21, No. 11 (2021), pp. 1143–1155.

Torabi, Elnaz., Aysin Dedekorkut-Howes and Michael Howes, "A framework for using the concept of urban resilience in responding to climate-related disasters", Urban Research and Practice, vol.15, No. 4 (2021). Available at DOI: 10.1080/17535069.2020.1846771

Tyler, Stephen and Marcus Moench, "A framework for urban climate resilience", Climate and Development, vol. 4, No. 4 (2012), pp. 311–326. Avaiable at DOI: 10.1080/17565529.2012.745389.

Urban Councils Association of Zimbabwe (2017). Service Level Benchmarking Peer Review 2017 Annual Report. Harare.

Van den Berg, Caroline., and Alexander Danilenko (2011). The IBNET Water Supply and Sanitation Performance Blue Book: The International Benchmarking Network for Water and Sanitation Utilities Databook. World Bank, Washington D.C., p. 176.

________ (2017). Performance of Water Utilities in Africa. World Bank, Washington, D.C.

van der Zaag, Pieter., and Hubert G. Savenije (2004). Principles of Integrated Water Resources Management. UNESCO-IHE Institute for Water Education. Delft, Netherlands.

Water and Sanitation Program (2011). Water Supply and Sanitation in Zimbabwe–Turning Finance Into Services for 2015 and Beyond. Working Paper, No. 72415. Washington D.C.: World Bank.

Westland, Jason. (2007). The Project Management Life Cycle: A Complete Step-by-Step Methodology for Initiating Planning Executing and Closing the Project. Kogan Page Publishers.

ZAMCOM-SADC-SARDC (2015). Zambezi Environment Outlook 2015. ZAMCOM, SADC, SARDC. Harare.

# APPENDIX A - Chapter 6

Table A1: Standard limits of basic items of surface water environmental quality standards (GB3838-2002) unit: mg/L

| No. | | Class I | Class II | Class III | Class IV | Class V |
|---|---|---|---|---|---|---|
| 1 | Water temperature () | The ambient water temperature caused by human should be limited to:<br>weekly average maximum temperature rise≤1<br>weekly average maximum temperature drop≤2 | | | | |
| 2 | pH (dimensionless) | 6~9 | | | | |
| 3 | Dissolved oxygen ≥ | saturation rate 90% (or 7.5) | 6 | 5 | 3 | 2 |
| 4 | Permanganate index ≤ | 2 | 4 | 6 | 10 | 15 |
| 5 | COD ≤ | 15 | 15 | 20 | 30 | 40 |
| 6 | $BOD_5$ ≤ | 3 | 3 | 4 | 6 | 10 |
| 7 | $NH_3$-N ≤ | 0.15 | 0.5 | 1.0 | 1.5 | 2.0 |
| 8 | TP (calculated by P) ≤ | 0.02 (Lake/Reservoir 0.01) | 0.1 (Lake/ Reservoir 0.025) | 0.2 (Lake/ Reservoir 0.05) | 0.3 (Lake/ Reservoir 0.1) | 0.4 (Lake/ Reservoir 0.2) |
| 9 | TN (Lake/reservoir, calculated by N) ≤ | 0.2 | 0.5 | 1.0 | 1.5 | 2.0 |
| 10 | Cu ≤ | 0.01 | 1.0 | 1.0 | 1.0 | 1.0 |
| 11 | Zn ≤ | 0.05 | 1.0 | 1.9 | 2.0 | 2.0 |
| 12 | Fluoride (calculated by $F^-$) ≤ | 1.0 | 1.0 | 1.0 | 1.5 | 1.5 |
| 13 | Se ≤ | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 |
| 14 | As ≤ | 0.05 | 0.05 | 0.05 | 0.1 | 0.1 |
| 15 | Hg ≤ | 0.00005 | 0.00005 | 0.0001 | 0.001 | 0.001 |
| 16 | Cd ≤ | 0.001 | 0.005 | 0.005 | 0.005 | 0.01 |
| 17 | Cr (hexavalent) ≤ | 0.01 | 0.05 | 0.05 | 0.05 | 0.1 |
| 18 | Pb ≤ | 0.01 | 0.01 | 0.05 | 0.05 | 0.1 |
| 19 | Cyanide ≤ | 0.005 | 0.05 | 0.2 | 0.2 | 0.2 |
| 20 | Volatile phenol ≤ | 0.002 | 0.002 | 0.005 | 0.01 | 0.1 |
| 21 | Petroleum ≤ | 0.05 | 0.05 | 0.05 | 0.5 | 1.0 |
| 22 | Anionic surfactant ≤ | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 |
| 23 | Sulfide ≤ | 0.05 | 0.1 | 0.2 | 0.5 | 1.0 |
| 24 | Fecal coliform (per/L) ≤ | 200 | 2 000 | 10 000 | 20 000 | 40 000 |

### Table A2: Standard limits for supplementary parameters of surface water sources of centralized domestic and drinking water (GB3838-2002) unit: mg/L

| No. | Event | Standard value |
|---|---|---|
| 1 | Sulfate (calculated by $SO_4^{2-}$) | 250 |
| 2 | Chloride (calculated by $Cl^-$) | 250 |
| 3 | Nitrate (calculated by N) | 10 |
| 4 | Fe | 0.3 |
| 5 | Mn | 0.1 |

### Table A3: Standard limits for specific projects of surface water sources for centralized drinking water (GB3838-2002) unit: mg/L

| No. | Item | Standard value | No. | Item | Standard value |
|---|---|---|---|---|---|
| 1 | Trichloromethane | 0.06 | 41 | Acrylamide | 0.0005 |
| 2 | Carbon tetrachloride | 0.002 | 42 | Acrylonitrile | 0.1 |
| 3 | Tribromomethane | 0.1 | 43 | Dibutyl phthalate | 0.003 |
| 4 | Dichloromethane | 0.02 | 44 | Bis(2-ethylhexyl) phthalate | 0.008 |
| 5 | 1,2-dichloromethane | 0.03 | 45 | Hydrazine Hydrate | 0.01 |
| 6 | Epichlorohydrin | 0.02 | 46 | Tetraethyl lead | 0.0001 |
| 7 | Vinyl chloride | 0.005 | 47 | Pyridine | 0.2 |
| 8 | 1,1-Dichloroethylene | 0.03 | 48 | Turpentine | 0.2 |
| 9 | 1,2-Dichloroethylene | 0.05 | 49 | Picric acid | 0.5 |
| 10 | Trichloroethylene | 0.07 | 50 | Butyl Xanthogen Acid | 0.005 |
| 11 | Perchloroethylene | 0.04 | 51 | Active chlorine | 0.01 |
| 12 | Chloroprene | 0.002 | 52 | DDT | 0.001 |
| 13 | Hexachlorobutadiene | 0.0006 | 53 | Lin Dan | 0.002 |
| 14 | Styrene | 0.02 | 54 | Heptachlor epoxy | 0.0002 |
| 15 | Formaldehyde | 0.9 | 55 | Parathion | 0.003 |
| 16 | Acetaldehyde | 0.05 | 56 | Methyl parathion | 0.002 |
| 17 | Acrolein | 0.1 | 57 | Malathion | 0.05 |
| 18 | Chloroacetaldehyde | 0.01 | 58 | Dimethoate | 0.08 |
| 19 | Benzene | 0.01 | 59 | Dichlorvos | 0.05 |

| No. | Item | Standard value | No. | Item | Standard value |
|---|---|---|---|---|---|
| 20 | Toluene | 0.7 | 60 | Trichlorfon | 0.05 |
| 21 | Ethylbenzene | 0.3 | 61 | O,O-diethyl S-(1-sulfanylbutyl) thiophosphate | 0.03 |
| 22 | Xylene [1] | 0.5 | 62 | Chlorothalonil | 0.01 |
| 23 | Cumene | 0.25 | 63 | Carbaryl | 0.05 |
| 24 | Chlorobenzene | 0.3 | 64 | Deltamethrin | 0.02 |
| 25 | 1,2-Dichlorobenzene | 1.0 | 65 | Atrazine | 0.003 |
| 26 | 1,4-Dichlorobenzene | 0.3 | 66 | Benzo(a)pyrene | $2.8\times10^{-6}$ |
| 27 | Trichlorobenzene [2] | 0.02 | 67 | Methylmercury | $1.0\times10^{-6}$ |
| 28 | Tetrachlorobenzene [3] | 0.02 | 68 | Polychlorinated biphenyls [6] | $2.0\times10^{-5}$ |
| 29 | Hexachlorobenzene | 0.05 | 69 | Microcystin-LR | 0.001 |
| 30 | Nitrobenzene | 0.017 | 70 | Phosphorus | 0.003 |
| 31 | Dinitrobenzene [4] | 0.5 | 71 | Mo | 0.07 |
| 32 | 2,4-Dinitrotoluene | 0.003 | 72 | Co | 1.0 |
| 33 | 2,4,6-Trinitrotoluene | 0.5 | 73 | Be | 0.002 |
| 34 | Nitrochlorobenzene [5] | 0.05 | 74 | B | 0.5 |
| 35 | 2,4-Dinitrochlorobenzene | 0.5 | 75 | Sb | 0.005 |
| 36 | 2,4-Dichlorophenol | 0.093 | 76 | Ni | 0.02 |
| 37 | 2,4,6-Trichlorophenol | 0.2 | 77 | Ba | 0.7 |
| 38 | Pentachlorophenol | 0.009 | 78 | V | 0.05 |
| 39 | Aniline | 0.1 | 79 | Ti | 0.1 |
| 40 | Benzidine | 0.0002 | 80 | Tl | 0.0001 |

Xylene: refers to p-xylene, m-xylene and o-xylene.
Trichlorobenzene: refers to 1,2,3-trichlorobenzene, 1,2,4-trichlorobenzene, 1,3,5-trichlorobenzene
Tetrachlorobenzene: refers to 1,2,3,4-tetrachlorobenzene, 1,2,3,5-tetrachlorobenzene, 1,2,4,5-tetrachlorobenzene.
Dinitrobenzene: refers to p-dinitrobenzene, m-dinitrobenzene, o-dinitrobenzene.
Nitrochlorobenzene: refers to p-nitrochlorobenzene, m-nitrochlorobenzene, o-nitrochlorobenzene.
Polychlorinated biphenyls: refers to PCB-1016, PCB-1221, PCB-1232, PCB-1242, PCB-1248, PCB-1254, PCB-1260

### Table A4: Conventional indicators and limits of groundwater quality (GB/T14848-2017)

| No. | Index | Class I | Class II | Class III | Class IV | Class V |
|---|---|---|---|---|---|---|
| Sensory traits and general chemical indicators | | | | | | |
| 1 | Colour (Platinum Diamond Chromaticity Unit) | ≤5 | ≤5 | ≤15 | ≤25 | 25 |
| 2 | Smell and taste | None | None | None | None | None |
| 3 | Turbidity /NTU[a] | ≤3 | ≤3 | ≤3 | ≤10 | 10 |
| 4 | Visible to the naked eye | None | None | None | None | None |
| 5 | pH | | | 6.5≤pH≤8.5 | 5.5≤pH6.5<br>8.5pH≤9.0 | pH5.5 or pH9.0 |
| 6 | Total hardness (calculated as $CaCO_3$)/(mg/L) | ≤150 | ≤300 | ≤450 | ≤650 | ≤650 |
| 7 | Total dissolved solids /(mg/L) | ≤300 | ≤500 | ≤1000 | ≤2000 | 2000 |
| 8 | Sulfate /(mg/L) | ≤50 | ≤150 | ≤250 | ≤350 | 350 |
| 9 | Chloride /(mg/L) | ≤50 | ≤150 | ≤250 | ≤350 | 350 |
| 10 | Fe/(mg/L) | ≤0.1 | ≤0.2 | ≤0.3 | ≤2.0 | 2.0 |
| 11 | Mn/(mg/L) | ≤0.05 | ≤0.05 | ≤0.10 | ≤1.50 | 1.50 |
| 12 | Cu/(mg/L) | ≤0.01 | ≤0.05 | ≤1.00 | ≤1.50 | 1.50 |
| 13 | Zn/(mg/L) | ≤0.05 | ≤0.5 | ≤1.00 | ≤5.00 | 5.00 |
| 14 | Al/(mg/L) | ≤0.01 | ≤0.05 | ≤0.20 | ≤0.50 | 0.50 |
| 15 | Volatile phenols (calculated as phenol)/(mg/L) | ≤0.001 | ≤0.001 | ≤0.002 | ≤0.01 | 0.01 |
| 16 | Anionic surfactant /(mg/L) | Not detectable | ≤0.1 | ≤0.3 | ≤0.3 | 0.3 |
| 17 | Oxygen consumption ($COD_{Mn}$ method, calculated by $O_2$) | ≤1.0 | ≤2.0 | ≤3.0 | ≤10.0 | 10.0 |
| 18 | Ammonia nitrogen (calculated as N)/(mg/L) | ≤0.02 | ≤0.10 | ≤0.50 | ≤1.50 | 1.50 |
| 19 | Sulfide /(mg/L) | ≤0.005 | ≤0.01 | ≤0.02 | ≤0.10 | 0.10 |
| 20 | Na/(mg/L) | ≤100 | ≤150 | ≤200 | ≤400 | 400 |
| microbiological indicators | | | | | | |
| 21 | Total coliform /(MPN[b] /100 mL or CFU[c] /100 mL) | ≤3.0 | ≤3.0 | ≤3.0 | ≤100 | 100 |
| 22 | Aerobic bacterial count /(CFU/ mL) | ≤100 | ≤100 | ≤100 | ≤1000 | 1000 |
| Toxicological indicators | | | | | | |

| No. | Index | Class I | Class II | Class III | Class IV | Class V |
|---|---|---|---|---|---|---|
| 23 | Nitrite (calculated as N)/(mg/L) | ≤0.01 | ≤0.10 | ≤1.00 | ≤4.80 | 4.80 |
| 24 | Nitrate (calculated as N)/(mg/L) | ≤2.0 | ≤5.0 | ≤20.0 | ≤30.0 | 30.0 |
| 25 | Cyanide /(mg/L) | ≤0.001 | ≤0.01 | ≤0.05 | ≤0.1 | 0.1 |
| 26 | Fluoride /(mg/L) | ≤1.0 | ≤1.0 | ≤1.0 | ≤2.0 | 2.0 |
| 27 | Iodide /(mg/L) | ≤0.04 | ≤0.04 | ≤0.08 | ≤0.50 | 0.50 |
| 28 | Hg/(mg/L) | ≤0.0001 | ≤0.0001 | ≤0.001 | ≤0.002 | 0.002 |
| 29 | As/(mg/L) | ≤0.001 | ≤0.001 | ≤0.01 | ≤0.1 | 0.1 |
| 30 | Se/(mg/L) | ≤0.01 | ≤0.01 | ≤0.01 | ≤0.1 | 0.1 |
| 31 | Cd/(mg/L) | ≤0.0001 | ≤0.001 | ≤0.005 | ≤0.01 | 0.01 |
| 32 | $Cr^{6+}$ /(mg/L) | ≤0.005 | ≤0.005 | ≤0.01 | ≤0.10 | 0.10 |
| 33 | Pb/(mg/L) | ≤0.005 | ≤0.005 | ≤0.01 | ≤0.10 | 0.10 |
| 34 | Trichloromethane/(μg/L) | ≤0.5 | ≤6 | ≤60 | ≤300 | 300 |
| 35 | Tetrachloromethane/(μg/L) | ≤0.5 | ≤0.5 | ≤2.0 | ≤50.0 | 50.0 |
| 36 | Benzene/(μg/L) | ≤0.5 | ≤1.0 | ≤10.0 | ≤120 | 120 |
| 37 | Toluene/(μg/L) | ≤0.5 | ≤140 | ≤700 | ≤1400 | 1400 |
| Radioactivity indicators [d] | | | | | | |
| 38 | Total α radioactivity (Bq/L) | ≤0.1 | ≤0.1 | ≤0.5 | 0.5 | 0.5 |
| 39 | Total β radioactivity (Bq/L) | ≤0.1 | ≤1.0 | ≤1.0 | 1.0 | 1.0 |

[a] NTU is the unit of scattered turbidity.

[b] MPN represents the most probable number.

[c] CFU stands for colony forming unit.

[d] Radionuclide analysis and evaluation should be performed if the radioactivity index exceeds the guideline value.

## Table A5: Unconventional indicators and limits of groundwater quality (GB/T14848-2017)

| No. | Index | Class I | Class II | Class III | Class IV | Class V |
|---|---|---|---|---|---|---|
| Toxicological indicators | | | | | | |
| 1 | Be/(mg/L) | ≤0.0001 | ≤0.0001 | ≤0.002 | ≤0.06 | 0.06 |
| 2 | B/(mg/L) | ≤0.02 | ≤0.10 | ≤0.50 | ≤2.00 | 2.00 |
| 3 | Sb/(mg/L) | ≤0.0001 | ≤0.0005 | ≤0.005 | ≤0.01 | 0.01 |
| 4 | Ba/(mg/L) | ≤0.01 | ≤0.10 | ≤0.70 | ≤4.00 | 4.00 |
| 5 | Ni/(mg/L) | ≤0.002 | ≤0.002 | ≤0.02 | ≤0.10 | 0.10 |
| 6 | Co/(mg/L) | ≤0.005 | ≤0.005 | ≤0.05 | ≤0.10 | 0.10 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | Mo/(mg/L) | ≤0.001 | ≤0.01 | ≤0.07 | ≤0.15 | 0.15 |
| 8 | Ag/(mg/L) | ≤0.001 | ≤0.01 | ≤0.05 | ≤0.10 | 0.10 |
| 9 | Th /(mg/L) | ≤0.0001 | ≤0.0001 | ≤0.0001 | ≤0.0001 | >0.0001 |
| 10 | Dichloromethane/(μg/L) | ≤1 | ≤2 | ≤20 | ≤500 | >500 |
| 11 | 1,2- dichloroethane/(μg/L) | ≤0.5 | ≤3.0 | ≤30.0 | ≤40.0 | >40.0 |
| 12 | 1,1,1- trichloroethane/(μg/L). | ≤0.5 | ≤400 | ≤2000 | ≤4000 | >4000 |
| 13 | 1,1,2- trichloroethane/(μg/L). | ≤0.5 | ≤0.5 | ≤5.0 | ≤60.0 | >60.0 |
| 14 | 1,2- dichloropropane/(μg/L) | ≤0.5 | ≤0.5 | ≤5.0 | ≤60.0 | >60.0 |
| 15 | Tribromomethane/(μg/L) | ≤0.5 | ≤10.0 | ≤100 | ≤800 | >800 |
| 16 | Vinyl chloride/(μg/L) | ≤0.5 | ≤0.5 | ≤5.0 | ≤90.0 | >90.0 |
| 17 | 1,1- dichloroethylene/(μg/L) | ≤0.5 | ≤3.0 | ≤30.0 | ≤60.0 | >60.0 |
| 18 | 1,2- dichloroethylene/(μg/L) | ≤0.5 | ≤5.0 | ≤50.0 | ≤60.0 | >60.0 |
| 19 | Trichloroethylene/(μg/L) | ≤0.5 | ≤7.0 | ≤70.0 | ≤210 | >210 |
| 20 | Tetrachloroethylene /(μg/L) | ≤0.5 | ≤4.0 | ≤40.0 | ≤300 | >300 |
| 21 | Chlorobenzene/(μg/L) | ≤0.5 | ≤60.0 | ≤300 | ≤600 | >600 |
| 22 | O-dichlorobenzene/(μg/L) | ≤0.5 | ≤200 | ≤1000 | ≤2000 | >2000 |
| 23 | P-dichlorobenzene/(μg/L) | ≤0.5 | ≤30.0 | ≤300 | ≤600 | >600 |
| 24 | Trichlorobenzene (total)/(μg/L)[a] | ≤0.5 | ≤4.0 | ≤20.0 | ≤180 | >180 |
| 25 | Ethylbenzene/(μg/L) | ≤0.5 | ≤30.0 | ≤300 | ≤600 | >600 |
| 26 | Xylene (total)/(μg/L)[b] | ≤0.5 | ≤100 | ≤500 | ≤1000 | >1000 |
| 27 | Styrene/(μg/L) | ≤0.5 | ≤2.0 | ≤20.0 | ≤40.0 | >40.0 |
| 28 | 2,4- dinitrotoluene/(μg/L). | ≤0.1 | ≤0.5 | ≤5.0 | ≤60.0 | >60.0 |
| 29 | 2,6- dinitrotoluene/(μg/L). | ≤0.1 | ≤0.5 | ≤5.0 | ≤30.0 | >30.0 |
| 30 | Naphthalene/(μg/L) | ≤1 | ≤10 | ≤100 | ≤600 | >600 |
| 31 | Anthracene/(μg/L) | ≤1 | ≤360 | ≤1800 | ≤3600 | >3600 |
| 32 | Fluoranthene/(μg/L) | ≤1 | ≤50 | ≤240 | ≤480 | >480 |
| 33 | Benzo (b) fluoranthene/(μg/L) | ≤0.1 | ≤0.4 | ≤4.0 | ≤8.0 | >8.0 |
| 34 | Benzo (a) pyrene/(μg/L) | ≤0.002 | ≤0.002 | ≤0.01 | ≤0.50 | >0.50 |
| 35 | PCBs (total)/(μg/L)[c] | ≤0.05 | ≤0.05 | ≤0.50 | ≤10.0 | >10.0 |
| 36 | Di (2- ethylhexyl) phthalate/(μg/L) | ≤3 | ≤3 | ≤8.0 | ≤300 | >300 |
| 37 | 2,4,6- trichlorophenol/(μg/L) | ≤0.05 | ≤20.0 | ≤200 | ≤300 | >300 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 38 | Pentachlorophenol/(μg/L) | ≤0.05 | ≤0.90 | ≤9.0 | ≤18.0 | >18.0 |
| 39 | BHC (total)/(μg/L)d | ≤0.01 | ≤0.50 | ≤5.00 | ≤300 | >300 |
| 40 | γ-BHC (Lindane)/(μg/L) | ≤0.01 | ≤0.20 | ≤2.00 | ≤150 | >150 |
| 41 | DDT (total)/(μg/L)e | ≤0.01 | ≤0.10 | ≤1.00 | ≤2.00 | >2.00 |
| 42 | Hexachlorobenzene/(μg/L) | ≤0.01 | ≤0.10 | ≤1.00 | ≤2.00 | >2.00 |
| 43 | Heptachlor/(μg/L) | ≤0.01 | ≤0.04 | ≤0.40 | ≤0.80 | >0.80 |
| 44 | 2,4- Dichlorophenoxyacetic acid/(μg/L) | ≤0.1 | ≤6.0 | ≤30.0 | ≤150 | >150 |
| 45 | Carbofuran/(μg/L) | ≤0.05 | ≤1.40 | ≤7.00 | ≤14.0 | >14.0 |
| 46 | Aldicarb/(μg/L) | ≤0.05 | ≤0.60 | ≤3.00 | ≤30.0 | >30.0 |
| 47 | Dichlorvos/(μg/L) | ≤0.05 | ≤0.10 | ≤1.00 | ≤2.00 | >2.00 |
| 48 | Methyl parathion/(μg/L) | ≤0.05 | ≤4.00 | ≤20.0 | ≤40.0 | >40.0 |
| 49 | Malathion/(μg/L) | ≤0.05 | ≤25.0 | ≤250 | ≤500 | >500 |
| 50 | Rogor/(μg/L) | ≤0.05 | ≤16.0 | ≤80.0 | ≤160 | >160 |
| 51 | Chlorpyrifos/(μg/L) | ≤0.05 | ≤6.00 | ≤30.0 | ≤60.0 | >60.0 |
| 52 | Chlorothalonil/(μg/L) | ≤0.05 | ≤1.00 | ≤10.0 | ≤150 | >150 |
| 53 | Atrazine/(μg/L) | ≤0.05 | ≤0.40 | ≤2.00 | ≤600 | >600 |
| 54 | Glyphosate/(μg/L) | ≤0.1 | ≤140 | ≤700 | ≤1400 | >1400 |

[a] Trichlorobenzene (total) is the sum of 3 isomers of 1,2,3- trichlorobenzene, 1,2,4- trichlorobenzene and 1,3,5- trichlorobenzene.

[b] Xylene (total) is the sum of 3 isomers of o-xylene, m-xylene and p-xylene.

[c] PCBs (total) is the sum of 9 polychlorinated biphenyls, namely PCB28, PCB52, PCB101, PCB118, PCB138, PCB153, PCB180, PCB194 and PCB206.

[d] BHC (total) is the sum of 4 isomers of α-BHC, β-BHC, γ-BHC and δ-BHC.

[e] DDT (total) is the sum of 4 isomers of o, p'- DDT, p, p'- Didi, p, p'- Didi and p, p'- DDT.

According to China's groundwater quality and human health risks, referring to the quality requirements of domestic drinking water, industry and agriculture, and according to the content of each component (except pH), it can be divided into five categories:

Class I: groundwater is low in chemical composition and suitable for various purposes.

Class II: groundwater is low in chemical composition and suitable for various purposes.

Class III: the chemical composition of groundwater is medium, which is based on GB5749-2006 and is mainly suitable for centralized drinking water sources and industrial and agricultural water.

Class IV: the groundwater has high chemical composition, which is based on the quality requirements of agricultural and industrial water and a presenting certain level of human health risks, and is suitable for agricultural and some industrial water, and can be used as drinking water after proper treatment.

Class V: groundwater is not suitable for drinking water because of its high chemical composition, and other water can be selected according to the purpose of use.

**Table A6: Routine water quality indicators and limits national standard (GB5749-2022)**

| 1. Microbial index | Limiting value |
|---|---|
| Total Coliform (MPN/100 mL or CFU/100 mL) | Not Detected |
| Thermotoletant coliform bacteria (MPN/100 mL or CFU/100 mL) | Not Detected |
| Escherichia coli (MPN/100 mL or CFU/100 mL) | Not Detected |
| Aerobic bacterial count (CFU/100 mL)100 | 100 |
| 2. Toxicological indicators | |
| As(mg/L) | 0. 01 |
| Cd (mg/L) | 0. 005 |
| Cr (hexavalent)(mg/L) | 0.05 |
| Pb (mg/L) | 0. 01 |
| Hg(mg/L) | 0. 001 |
| Cyanide(mg/L) | 0.05 |
| Fluoride(mg/L) | 1.0 |
| Azotate (Calculated as N element)(mg/L) | 10 Underground water limit is 20 |
| Trichloromethane(mg/L) | 0.06 |
| Bromate (when using ozone)(mg/L) | 0.01 |
| Chlorite (when disinfecting with chlorine dioxide)(mg/L) | 0.7 |
| Chlorate (when disinfecting with combined chlorine dioxide)(mg/L) | 0.7 |
| 3. Sensory traits and general chemical indicators | |
| Chroma (platinum cobalt colour unit) | 15 |
| turbidity/NTU | 1 (3 when water source and water purification technology conditions are limited) |
| Odour and taste | No odour |
| Visible to the naked eye | Not Detected |
| pH | $6.5 \leq pH \leq 8.5$ |
| Al (mg/L) | 0.2 |
| Fe (mg/L) | 0.3 |
| Mn (mg/L) | 0.1 |
| Cu (mg/L) | 1.0 |
| Zn (mg/L) | 1.0 |
| Chloride(mg/L) | 250 |

| | |
|---|---|
| Sulfate(mg/L) | 250 |
| Total dissolved solids(mg/L) | 1000 |
| Total hardness(mg/L) | 450 |
| Oxygen consumption(mg/L) | 3 Water source limitation: 5 when the oxygen consumption of raw water is more than 6 mg / L |
| Volatile phenols (Calculated as phenol)(mg/L) | 0.002 |
| Anionic synthetic detergent(mg/L) | 0.3 |
| 4 Radioactivity index | |
| Total α activity(Bq/L) | 0.5 |
| Total β activity(Bq/L) | 1 |

## Table A7: General index of disinfectant (GB5749-2022)

| Name of disinfectant | Contact time with water | Ex-factory water limit(mg/L) | Factory water allowance(mg/L) | Water allowance at the end of pipe network(mg/L) |
|---|---|---|---|---|
| Chlorine and Free Chlorine Preparations (Free Chlorine) | ≥30min | ≤2 | ≥0.3 | ≥0.05 |
| Monochloramine (total chlorine) | ≥120min | ≤3 | ≥0.5 | ≥0.05 |
| Ozone | ≥12min | ≤0.3 | —— | ≥0.02 if other cooperative disinfection methods are adopted, the limit and surplus of disinfectant shall meet the corresponding requirements |
| Chlorine dioxide | ≥30min | ≤0.8 | ≥0.1 | ≥0.02 |

## Table A8: Extended index and limit of drinking water quality (GB5749-2022)

| Index | limiting value |
|---|---|
| 1. Microbial index | |
| Giardia/(number/10 L) | 1 |
| Cryptosporidium/(number/10 L) | 1 |
| 2.Toxicological indicators | |
| Sb/(mg/L) | 0.005 |
| Ba/(mg/L) | 0.7 |

| | |
|---|---|
| Be/(mg/L) | 0.002 |
| B/(mg/L) | 1.0 |
| Mo/(mg/L) | 0.07 |
| Ni/(mg/L) | 0.02 |
| Ag/(mg/L) | 0.05 |
| Tl/(mg/L) | 0.0001 |
| Se/(mg/L) | 0.01 |
| Perchlorate/(mg/L) | 0.07 |
| Dichloromethane/(mg/L) | 0.02 |
| 1,2-dichloroethane/(mg/L) | 0.03 |
| Carbon tetrachloride/(mg/L) | 0.002 |
| Vinyl chloride/(mg/L) | 0.001 |
| 1,1-dichloroethylene/(mg/L) | 0.03 |
| 1,2-dichloroethylene(total)/(mg/L) | 0.05 |
| Trichloroethylene/(mg/L) | 0.02 |
| Tetrachloroethylene/(mg/L) | 0.04 |
| Hexachlorobutadiene/(mg/L) | 0.0006 |
| Triclosan/(mg/L) | 0.1 |
| Trichloroacetaldehyde /(mg/L) | 0.01 |
| 2,4,6-trichlorophenol/(mg/L) | 0.2 |
| Bromoform/(mg/L) | 0.1 |
| Heptachlor/(mg/L) | 0.0004 |
| Malathion/(mg/L) | 0.25 |
| Pentachlorophenol/(mg/L) | 0.009 |
| Benzene/(mg/L) | 0.01 |
| Methylbenzene/(mg/L) | 0.7 |
| Dimethylbenzene (total)/(mg/L) | 0.5 |
| Styrene/(mg/L) | 0.3 |
| 1,4-dichlorobenzene/(mg/L) | 0.3 |
| Trichlorobenzene (total)/(mg/L) | 0.02 |
| Hexachlorobenzene/(mg/L) | 0.001 |

| | |
|---|---|
| Heptachlor/(mg/L) | 0.0004 |
| Malathion/(mg/L) | 0.25 |
| Dimethoate/(mg/L) | 0.006 |
| Bentazone/(mg/L) | 0.3 |
| Chlorothalonil/(mg/L) | 0.01 |
| Carbofuran/( mg/L) | 0.007 |
| Chlorpyrifos/( mg/L) | 0.03 |
| Glyphosate/(mg/L) | 0.7 |
| Dichlorvos/(mg/L) | 0.001 |
| Atrazine/(mg/L) | 0.002 |
| Deltamethrin/(mg/L) | 0.02 |
| 2,4-Dichlorophenoxyacetic acid/(mg/L) | 0.03 |
| Acetochlor/(mg/L) | 0.02 |
| Pentachlorophenol/(mg/L) | 0.009 |
| 2,4,6-trichlorophenol/(mg/L) | 0.2 |
| Benzo(a)pyrene/(mg/L) | 0.00001 |
| Bis (2-ethylhexyl) phthalate/(mg/L) | 0.008 |
| Acrylamide/(mg/L) | 0.0005 |
| Epichlorohydrin/(mg/L) | 0.0004 |
| Microcystis cord –LR(When algae outbreak occurs)/(mg/L) | 0.001 |
| 3. Sensory traits and general chemical indicators | |
| Na/(mg/L) | 200 |
| Volatilized Phenol (Calculated as phenol)/(mg/L) | 0.002 |
| Anionic synthetic detergent/(mg/L) | 0.3 |
| 2-methylisopropanol/(mg/L) | 0.00001 |
| Geosmin/(mg/L) | 0.00001 |

## Table A9: Reference index and limit of drinking water quality (GB5749-2022)

| Index | limiting value |
|---|---|
| Enterococcus/(MPN/100 mL or CFU/100 mL) | Not Detected |
| Clostridium Perfringens/(CFU/100 mL) | Not Detected |
| V /(mg/L) | 0.01 |
| Ethylmercuric Chloride/(mg/L) | 0.0001 |
| Tetraethyl lead/(mg/L) | 0.0001 |
| Benzene Hexachloride(total)/(mg/L) | 0.005 |
| Parathion/(mg/L) | 0.003 |
| Methyl-parathion/(mg/L) | 0.009 |
| Lindane/(mg/L) | 0.002 |
| DDT/(mg/L) | 0.001 |
| Trichlorfon/(mg/L) | 0.05 |
| Thiophanate methyl/(mg/L) | 0.3 |
| Isoprothiolane/(mg/L) | 0.3 |
| Trifluralin/(mg/L) | 0.02 |
| Metalaxyl/(mg/L) | 0.05 |
| Simetryne/(mg/L) | 0.03 |
| Acephate/(mg/L) | 0.08 |
| Formaldehyde/(mg/L) | 0.9 |
| Trichloroacetaldehyde/(mg/L) | 0.1 |
| Cyanogen chloride (Calculated as $CN^-$)/(mg/L) | 0.07 |
| Nitrosodimethylamine/(mg/L) | 0.0001 |
| Iodoacetic acid/(mg/L) | 0.02 |
| 1,1,1-trichloroethane/(mg/L) | 2 |
| 1,2-dibromoethane/(mg/L) | 0.00005 |
| Pentachloropropane/(mg/L) | 0.03 |
| Ethylbenzene/(mg/L) | 0.3 |
| 1,2-dichlorobenzene/(mg/L) | 1 |
| Nitrobenzene/(mg/L) | 0.017 |
| BPA(bisphenol A)/(mg/L) | 0.01 |

| | |
|---|---|
| Acrylonitrile/(mg/L) | 0.1 |
| Acrolein/(mg/L) | 0.1 |
| Glutaraldehyde/(mg/L) | 0.07 |
| Tris (2-ethylhexyl) adipic acid ester/(mg/L) | 0.4 |
| Diethyl phthalate/(mg/L) | 0.3 |
| Dibutyl phthalate/(mg/L) | 0.003 |
| Polyaromatic hydrocarbon (total)/(mg/L) | 0.002 |
| Polychlorinated biphenyl (total)/(mg/L) | 0.0005 |
| Dioxin (2,3,7,8-TCDD)/(mg/L) | 0.00000003 |
| Perfluorooctanoic acid/(mg/L) | 0.00008 |
| Perfluorooctane sulfonic acid/(mg/L) | 0.00004 |
| Acrylic acid/(mg/L) | 0.5 |
| Naphthenic acid/(mg/L) | 1 |
| Butyl xanthic acid/(mg/L) | 0.001 |
| Beta-naphthol/(mg/L) | 0.4 |
| Dimethyl disulfide/(mg/L) | 0.00003 |
| Dimethyl trisulfide/(mg/L) | 0.00003 |
| Anisole/(mg/L) | 0.05 |
| Petroleum (total)/(mg/L) | 0.05 |
| TOC/(mg/L) | 5 |
| Iodide/(mg/L) | 0.1 |
| Sulfide/(mg/L) | 0.02 |
| Propylene cyanide/(mg/L) | 0.1 |
| Nitrite (Calculated as N element)/(mg/L) | 1 |
| Asbestos (10μm)/(ten thousand/L) | 700 |
| U/(mg/L) | 0.03 |
| Ra-226/(Bq/L) | 1 |

### Table A10: Routine water quality indicators and limits Shanghai standard (DB31/T1091-2018)

| Index | limiting value |
|---|---|
| 1. Microbial index | |
| Total Coliform (MPN/100 mL or CFU/100 mL) | Not Detected |
| Thermotoletant coliform bacteria (MPN/100 mL or CFU/100 mL) | Not Detected |
| Escherichia coli (MPN/100 mL or CFU/100 mL) | Not Detected |
| Aerobic bacterial count (CFU/mL) | ≤50 |
| 2. Toxicological indicators | |
| As (mg/L) | ≤0. 01 |
| Cd (mg/L) | ≤0. 003 |
| Cr (hexavalent)(mg/L) | ≤0. 05 |
| Pb (mg/L) | ≤0. 01 |
| Hg (mg/L) | ≤0. 0001 |
| Se (mg/L) | ≤0. 01 |
| Sb (mg/L) | ≤0. 005 |
| Cyanide (mg/L) | ≤0. 05 |
| Fluoride (mg/L) | ≤1.0 |
| Azotate (Calculated as N element) (mg/L) | ≤10 |
| Nitrite nitrogen (mg/L) | ≤0.15 |
| Trichloromethane (mg/L) | ≤0.06 |
| Bromodichloromethane solution (mg/L) | ≤0.1 |
| Trichloromethane (mg/L) | ≤0. 06 |
| Bromoform (mg/L) | ≤0.1 |
| Trihalomethane (mg/L) | Sum of ratios of measured concentrations of various compounds to their limits ≤0.5 |
| Carbon tetrachloride (mg/L) | ≤0.002 |
| Bromate (when using ozone) (mg/L) | ≤0.005 |
| Formaldehyde (when using ozone) (mg/L) | ≤0.45 |
| Chlorite (when disinfecting with chlorine dioxide) (mg/L) | ≤0.7 |
| Chlorate (when disinfecting with combined chlorine dioxide) (mg/L) | ≤0.7 |
| 3. Sensory traits and general chemical indicators | |

| | |
|---|---|
| Chroma (platinum cobalt colour unit) | ≤10 |
| turbidity/NTU | ≤0. 5 |
| Odour and taste | No odour |
| Visible to the naked eye | Not Detected |
| pH | 6.5≤pH≤8.5 |
| Al (mg/L) | ≤0.2 |
| Fe (mg/L) | ≤0. 2 |
| Mn (mg/L) | ≤0. 05 |
| Cu (mg/L) | ≤1.0 |
| Zn (mg/L) | ≤1.0 |
| Chloride(mg/L) | ≤250 |
| Sulfate(mg/L) | ≤250 |
| Total dissolved solids(mg/L) | ≤500 |
| Total hardness(mg/L) | ≤250 |
| oxygen consumption(mg/L) | ≤2 Water source limitation: 3 when the oxygen consumption of raw water is more than 4 mg / L |
| Volatile phenols (Calculated as phenol)(mg/L) | ≤0. 002 |
| Anionic synthetic detergent(mg/L) | ≤0. 2 |
| ammonia nitrogen (Calculated as N element)(mg/L) | ≤0. 5 |
| 4. Radioactivity index | |
| Total alpha activity(Bq/L) | ≤0. 5 |
| Total beta activity(Bq/L) | ≤1 |
| 5. Disinfectant index | |
| Free Chlorine | Contact time with water≥30min0.5mg/L ≤Factory water allowance≤2mg/LWater allowance at the end of pipe network≤0.05mg/L |
| Total chlorine | Contact time with water≥120min0.5mg/L ≤Factory water allowance≤2mg/LWater allowance at the end of pipe network≤0.05mg/L |
| Ozone | Contact time with water≥12minFactory water allowance≤0.3mg/LWater allowance at the end of pipe network≤0.02mg/Lif chlorine injectiontotal chlorine≥0.05 |
| Chlorine dioxide | Contact time with water≥30min0.1mg/L≤ Factory water allowance≤0.8mg/LWater allowance at the end of pipe network≤0.02mg/L |

**Table A11: Unconventional indicators and limits of water quality (DB31/T1091-2018)**

| Microbial index | limiting value |
|---|---|
| Giardia/(number/10 L) | <1 |
| Cryptosporidium/(number /10 L) | <1 |
| Toxicological indicators | |
| Ba/(mg/L) | ≤0.7 |
| Be/(mg/L) | ≤0.002 |
| B/(mg/L) | ≤0.5 |
| Mo/(mg/L) | ≤0.07 |
| Ni/(mg/L) | ≤0.02 |
| Ag/(mg/L) | ≤0.05 |
| Th/(mg/L) | ≤0.0001 |
| Cyanide chloride/(mg/L) | ≤0.035 |
| Dichloroacetic acid/(mg/L) | ≤0.025 |
| 1,2-dichloroethane/(mg/L) | ≤0.003 |
| Dichloromethane/(mg/L) | ≤0.005 |
| 1,1,1 trichloroethane(mg/L) | ≤0.2 |
| Bromoform/(mg/L) | ≤0.1 |
| Heptachlor/(mg/L) | ≤0.0004 |
| Malathion/(mg/L) | ≤0.25 |
| Triclosan/(mg/L) | ≤0.05 |
| Trichloroacetaldehyde/(mg/L) | ≤0.005 |
| 2,4,6-trichlorophenol/(mg/L) | ≤0.1 |
| Pentachlorophenol/(mg/L) | ≤0.001 |
| Benzex (total)/(mg/L) | ≤0.005 |
| Hexachlorobenzene/(mg/L) | ≤0.001 |
| Dimethoate/(mg/L) | ≤0.006 |
| Parathion/(mg/L) | ≤0.003 |
| Bentazone/(mg/L) | ≤0.3 |
| Parathion-methyl/(mg/L) | ≤0.02 |
| Chlorothalonil/(mg/L) | ≤0.01 |

| | |
|---|---|
| Carbofuran/( mg/L) | ≤0.007 |
| Lindane/(mg/L) | ≤0.0002 |
| Chlorpyrifos/(mg/L) | ≤0.03 |
| Glyphosate/(mg/L) | ≤0.7 |
| Dichlorvos/(mg/L) | ≤0.001 |
| Atrazine/(mg/L) | ≤0.002 |
| Deltamethrin/(mg/L) | ≤0.02 |
| 2,4-Dichlorophenoxyacetic acid/(mg/L) | ≤0.03 |
| Dichlorodiphenyl Trichloroethane/(mg/L) | ≤0.001 |
| Ethylbenzene/(mg/L) | ≤0.3 |
| Xylene/(mg/L) | ≤0.7 |
| 1,1-Dichloroethylene/(mg/L) | ≤0.007 |
| 1,2- Dichloroethylene/(mg/L) | ≤0.05 |
| 1,2- Dichlorobenzene/(mg/L) | ≤0.6 |
| 1,4- Dichlorobenzene/(mg/L) | ≤0.075 |
| Trichloroethylene/(mg/L) | ≤005 |
| Trichlorobenzene/(mg/L) | ≤0.02 |
| Hexachlorobutadiene/(mg/L) | ≤0.0006 |
| Acrylamide/(mg/L) | ≤0.0001 |
| Tetrachloroethylene/(mg/L) | ≤0.005 |
| Toluene/(mg/L) | ≤0.7 |
| Phthalates/(mg/L) | ≤0.006 |
| Chloropropane oxide/(mg/L) | ≤0.0001 |
| Benzene/(mg/L) | ≤0.001 |
| Styrene/(mg/L) . | ≤0.02 |
| Benzene (a) xenon/(mg/L) | ≤0.00001 |
| Vinyl chloride/(mg/L) | ≤0.0003 |
| Chlorobenzene/(mg/L) | ≤0.1 |
| Microcystis cord -LR/(mg/L) | ≤0.001 |
| N-Nitrosodimethylamine/(mg/L) | ≤0.0001 |
| Sensory traits and general chemical indicators - Unconventional | |

| | |
|---|---|
| Sulfide/(mg/L) | ≤0.02 |
| Sodium/(mg/L) | ≤200 |
| 2-Methylisoborneol/(mg/L) | ≤0.00001 |
| Geosmin/(mg/L) | ≤0.00001 |
| TOC/(mg/L) | ≤3 |

### Table A12: PAC for treatment of drinking water (GB15892-2020)

| **Index**<br>**The mass fraction of $Al_2O_3$/%**<br>**Basicity/%** | **State** | |
|---|---|---|
| | Liquid | Solid |
| | ≥10.0 | ≥29.0 |
| | 45.0 ~ 90.0 | |
| Density(20)/(g/cm$^3$) | ≥1.12 | – |
| The mass fraction of insoluble matter/% | ≤0.1 | |
| pH value (10g/L aqueous solution) | 3.5 ~ 5.0 | |
| The mass fraction of Fe/% | ≤0.2 | |
| The mass fraction of As/% | ≤0.0001 | |
| The mass fraction of Pb/% | ≤0.0005 | |
| The mass fraction of Cd/% | ≤0.0001 | |
| The mass fraction of Hg/% | ≤0.00001 | |
| The mass fraction of Cr/% | ≤0.0005 | |
| The mass fractions of insoluble matter, Fe, As, Pb, Cd, Hg and Cr of the products listed in the table are calculated according to the $Al_2O_3$ content of 10.0%. When the $Al_2O_3$ content is more than 10.0%, it shall be converted into the product proportion of $Al_2O_3$ of 10.0% according to the actual content, and the corresponding mass fraction shall be calculated. The product shall also comply with relevant national laws, regulations and mandatory standards. | | |

### Table A13: SPFS for water treatment (GB/T 14591-2016)

| Items | | Index | | | |
|---|---|---|---|---|---|
| | | First class products | | Qualified products | |
| | | Liquid | Solid | Liquid | Solid |
| The mass fraction of total iron $w_1$/% | ≥ | 11.0 | 19.5 | 11.0 | 19.5 |
| The mass fraction of reducing substances (calculated by $Fe^{2+}$) $w_2$/% | ≤ | 0.10 | 0.15 | 0.10 | 0.15 |
| Basicity $w_3$/% | | 8.0 ~ 16.0 | | 5.0 ~ 20.0 | |
| pH value (10g/L aqueous solution) | | 1.5 ~ 3.0 | | | |
| Density (20)/(g/cm³) | ≥ | 1.45 | — | 1.45 | — |
| The mass fraction of insoluble matter $w_4$/% | ≤ | 0.2 | 0.4 | 0.3 | 0.6 |
| The mass fraction of As $w_5$/% | ≤ | 0.0001 | 0.0002 | 0.0005 | 0.001 |
| The mass fraction of Pb $w_6$/% | ≤ | 0.0002 | 0.0004 | 0.001 | 0.002 |
| The mass fraction of Cd $w_7$/% | ≤ | 0.00005 | 0.0001 | 0.00025 | 0.0005 |
| The mass fraction of Hg $w_8$/% | ≤ | 0.00001 | 0.00002 | 0.00005 | 0.0001 |
| The mass fraction of Cr $w_9$/% | ≤ | 0.0005 | 0.001 | 0.0025 | 0.005 |
| The mass fraction of Zn $w_{10}$/% | ≤ | | — | 0.005 | 0.01 |
| The mass fraction of Ni $w_{11}$/% | ≤ | | — | 0.005 | 0.01 |
| When the first class product is used for drinking water treatment, it shall meet the requirements of code for health and safety evaluation of chemical treatment agents for drinking water and relevant laws and regulations. | | | | | |

# APPENDIX B - About the authors

## Prof Dr Thomas Chiramba

Prof Dr Thomas Chiramba holds a PhD in Civil Engineering (Municipal Engineering) and a Master's Degree in Architecture from Technical Universities of Karlsruhe and Aachen respectively, both in Germany as well as postgraduate qualifications from the University of Pennsylvania in the USA.

He has over 35 years of experience in water and the environment, sustainable infrastructure development and urban development and management. His experience stretches from research, to hands on technical work for a rapidly growing City right through to policy review and policy formulation at national, regional and global levels.

Currently, he is Adjunct Professor at the Namibia University of Science and Technology (NUST) in Namibia; University of Strathclyde, UK; and Tongji University, China. He worked for the UN for over 20 years. With the UN, Thomas did extensive work on water, infrastructure development and the environment. He worked for several years as the Chief Technical Advisor for the United Nations Development Program (UNDP) to the Southern African Development Community (SADC) overseeing the implementation of the Regional Strategic Action Programme on Water. He also worked for the United Nations Environment Programme (UNEP) as Deputy Coordinator of its global Dams and Development Programme. He was appointed Chief of the Freshwater Ecosystems Unit by UNEP, a post he held for over 10 years before joining the United Nations Human Settlements Program
(UN Habitat). Thomas contributed to the development of the Sustainable Development Goals through his membership of UN Water.

Whilst with (UN Habitat), his work focused on urban development and management. In his immediate position prior to retirement in 2021, Thomas worked as Senior Human Settlements Advisor in the Regional Office for Africa where he managed country programmes of 12 Eastern and Southern African Countries. He advised central and local governments as they developed and implemented Habitat Country Programs to achieve sustainable urban development. Early in his career, he was City Engineer for Kwekwe Municipality in Zimbabwe before assuming technical advisory positions with the United States International Development Agency (USAID) and the German Technical Cooperation (GIZ) providing managerial input to a large national housing program in Zimbabwe and a big urban development project that established five new municipalities in northern Namibia respectively.

## Eng Joel Balagizi Asipingwe

Eng Joel Balagizi Asipingwe holds a Bachelors in Civil Engineering from Hope Africa University in Burundi and a Masters degree in Architecture from North China University of Technology in China. He is currently a Doctoral candidate in the College of Environmental Science and Engineering at Tongji University in China.

Previously, up to 2022, Joel worked as an Urban Expert in the Regional Office for Africa at UN Habitat supporting and facilitating the development as well as day to day implementation of urban projects of UN-Habitat in a number of eastern and southern African countries. He also coordinated the Regional Office for Africa's collaboration with Tongji University.

## Prof Innocent Nhapi

Prof Innocent Nhapi is a freelance consultant in sanitary and environmental engineering, institutional development, integrated water resources management, and water and climate development. He holds a Bachelor of Technology (Civil Engineering) degree and a Post-graduate Diploma in Project Planning and Management from the University of Zimbabwe, a Diploma in Business Administration from the Zimbabwe Institution of Management, a Master of Science from University of Technology Sydney (Australia) and a Doctor of Philosophy from UNESCO-IHE Institute for Water Education (Netherlands). His work experience includes 10 years municipal engineering and 22 years in the academic and capacity development sector.

## Prof Faustin Kalabamu

Prof Faustin Kalabamu is Professor of Urban Planning at the University of Botswana. He holds a Doctorate in Architecture, Town and Regional Planning from the University of KwaZulu-Natal, South Africa; a Master of Philosophy degree in Urban Design and Regional Planning, University of Edinburgh, United Kingdom; and an Advanced Diploma in Urban and Regional Planning from Ardhi Institute, Tanzania. He has over 40 years of international work experience having worked in Bangladesh, Botswana, Tanzania, and Zimbabwe. He has over 80 publications on urban planning, housing, gender, and land issues.

## Dr Dube Tisetso

Dr Dube Tisetso is a Lecturer at the National University of Science and Technology, Bulawayo, Zimbabwe, in the Faculty of the Built Environment, Department of Property Studies and Urban Design. He holds a Bachelor of Science Rural and Urban Planning, Master of Science in Rural and Urban Planning from the University of Zimbabwe and a Doctor of Philosophy in Urban and Regional Planning from the University of Free State, South Africa. His work experience includes 9 years in consultancy, 13 years within local authorities, 3 years in non-governmental organizations, and 3 years in academia. His research interests include urban governance and planning and urban informality. In terms of country work experience this includes Zimbabwe, Botswana & Zambia.

## Dr Odirile Phillimon Tlamelo

Dr Odirile Phillimon Tlamelo is a qualified civil and environmental engineer holding a Master of Science degree in Water and Wastewater Engineering from the Kharkov Institute of Civil Engineering (Ukraine). He also holds a Doctorate in Chemical and Process Engineering from University of Newcastle upon Tyne (United Kingdom). He has about 25 years of water and environmental engineering working experience as a consultant with various companies and as lecturer at Botswana Polytechnic and University of Botswana. He is currently a Senior lecturer and head of the Civil Engineering Department, Faculty of Engineering and Technology, University of Botswana where he is teaching environmental engineering courses to undergraduate and postgraduate students. He is a Professional Member: Water Environment Federation, USA, (# 17776258) and also a Member of the International Association for Hydro-Environment Engineering and Research, (# **88001).**

## Prof Moalafhi Ditiro Benson

Prof Moalafhi Ditiro Benson is a hydrologist and water resources management expert with over 20 years of experience as an academic and a civil servant. He holds a Doctorate in Civil and Environmental Engineering (Hydro-climatology) from The University of New South Wales, Sydney, Australia (in 2016); a Master of Philosophy in Environmental Science (in 2004), Postgraduate Diploma in Education (in 2001) and a Bachelor of Science degree specializing in Environmental Science (in 2000) all from the University of Botswana. His research interests are in (i) water resources management and systems analysis, (ii) runoff generation and river flow regime changes and their evolution under changing drainage and climate, (iii) drought and low flow characterization, and (iv) climate reconstruction for hydrological applications.

Professor Moalafhi is currently an Associate Professor of water resources management at Botswana University of Agriculture and Natural Resources, since March 2022. He is currently the Acting Head of Wildlife and Aquatic Resources and holds the position of SASSCAL Research Chair in Water Resource Quantity and Availability.

## Eng Kelvin Chitumbo

**Engineering Registration Board Nomination**

Eng Kelvin Chitumbo is the director (CEO) of the National Water Supply and Sanitation Council (NWASCO) in Zambia. He is an engineer and water regulation expert with more than 18 years of experience in water utility regulation and reform, policy development, restructuring and organization development, financing and services provision. His current roles include Planning, controlling, coordinating and implementing the strategic goals and objectives of NWASCO in collaboration with the chairman of the Council, to enable the Council fulfill its governance function and provide direction to leadership towards consistent achievement of the organization's philosophy, mission, strategy, annual goals and objectives.

## Dr Wilma Nchito

Dr Wilma Nchito is a senior lecturer in the Department of Geography and Environmental Studies, School of Natural Sciences, University of Zambia. Her specializations are urban geography, water and environment management, and tourism. She has taught various courses in these fields at undergraduate and postgraduate levels. Some of these are urban Geography; tourism, development and the environment; and planning for Zambian's Urban Future. Her research and publications cover informality in cities, climate change and cities, small town development, urban flooding, water and sanitation in particular. She has studied the impacts of extreme climatic events on tourism, cities, and hazards such as flooding or scarcity of water supply when there are incidences of drought. She has been instrumental in ensuring that climate change and its impacts on planning as well as urban ecology are infused into existing courses. She has also researched on horticultural value chains and food systems. Dr. Nchito is currently the Director of Research and Graduate Studies at the University of Zambia.

## Dr Godfrey Tichaona Pazvakawambwa

Dr Godfrey Tichaona Pazvakawambwa (Phd in Civil, MZwe) currently employed by Namibia Water Corporation for the last 14 years as manager, infrastructure planning, has 30 years of experience in the Southern African region in the planning of water infrastructure, development and management of water resources as well as supervising students in related research topics.

## Plan Petrine Sem

Plan Petrine Sem (Masters in Town, Regional Planning and Development) is currently self-employed at Dunamis Consulting (Pty) Ltd. Previously, she was employed by the City of Windhoek from 2004 till 2016 as a town planner in training up to becoming a senior town planner. She has 18 years of experience in strategic structure plans, town planning schemes, regulations, policy formulations, economic development initiatives, spatial planning in layout planning and township establishments.

## Prof Dr Fengting Li

Prof Dr Fengting Li is the Fellow of the African Academy of Science and Director of Key Laboratory of Cities' Mitigation and Adaptation to Climate Change in Shanghai. As an expert on drinking water and wastewater treatment, he led the China Chemicals Alliance for Water Treatment. He owns more than 30 patents, and published more than 100 papers on peer-reviewed international journals. Professor Li has a Bachelor's degree of applied chemistry from Beijing Institute of Technology (1986), a Master's degree from Shandong Polytechnic University (1989), and a Doctoral degree from Nanjing University (1997), China. He was a visiting scholar to the University of Georgia and the Free University of Berlin, Germany.

## Dr Jianguo Tan

Dr Jianguo Tan is the director of and a professor at the Shanghai Climate Center. He is also Co-Director of Key Laboratory of Cities' Mitigation and Adaptation to Climate Change in Shanghai jointly built by Tongji University and Shanghai Meteorological Service. Previously, he was the director of Shanghai Institute of Meteorological Science, as well as the director of Shanghai Municipal Key Laboratory of Meteorology and Health. His research interests include urban climatology, urban micrometeorology, boundary layer meteorology, urban environment and urban climate change and human health.

## Assoc Prof Hongtao Wang

Assoc Prof Hongtao Wang is an associate professor at Tongji University. He teaches in the College of Environmental Science and Engineering of Tongji University and at the UNEP-Tongji Institute of Environment for Sustainable Development. Dr. Wang´s research fields include water resources management and water treatment. In the past years, Dr. Wang has been involved in the Africa-China Cooperation Programme on Environment, which is supported by the Ministry of Science and Technology of China and coordinated by the United Nations Environment Programme. He contributed to the implementation of a drinking water treatment project and a wastewater treatment project in Kenya.

## Dr Qian Jia

Dr Qian Jia is working in the Institute of Environment for Sustainable Development, a partnership between UNEP and Tongji University, as the manager for research and outreach. Prior to this position, she worked as a consultant for South-South Cooperation at UNEP headquarters in Nairobi, Kenya, from 2014–2016. Her research area is in circular economy, behavioural science for sustainability, education for sustainable development, with a focus on developing countries and regions.

## Prof Dr Ying Wang

Prof Dr Ying Wang is the vice dean of the School of Environmental Science and Engineering of Tongji University, and vice dean of Institute of Environment for Sustainable Development, a partnership between UNEP and Tongji. She graduated from Wuhan University with Bachelor of Science in 2007 and with a Doctor of Philosophy from Tsinghua University in 2012. She worked at Pacific Northwest National Laboratory, United States, from 2009 to 2011 during her doctoral study and at the East China University of Science and Technology in her postdoctoral period from 2012 to 2014. Then, she joined Tongji University in 2015. She has published over 30 peer-reviewed papers, including more than 15 papers with impact factor over 5.0.

# Endnotes

1 Racial discriminatory law imposed by the ruling European population on the movement of Africans into urban areas.

2 Department of Civil Engineering, University of Botswana

3 Department of Wildlife & Aquatic Resources. Botswana University of Agric & Nat Res. (BUAN)

4 Department of Architecture and Planning, University of Botswana

5 A small grassy floodplain of central Africa

6 Key Laboratory of Cities' Mitigation and Adaptation to Climate Change in Shanghai (CMACC)

7 College of Enviornmental Science and Engineering, Tongji University,China

8 Independent Researcher, 11 Msasa Drive, Mzari Township, Chinhoyi, Zimbabwe

9 Hot day means daily maximum temperature is above 35º.

10 High temperature strength refers to the average daily maximum in hot days.

11 The longest continuous high temperature days refers to the days when the temperature is continuously higher than 35º.

12 The flood season in Shanghai is from June to September.

13 The goal of refined management of water supply to improve engineering standards for the construction of water supply facilities. These advances can be achieved by revamping the governance of water resources and establishing an efficient urban water supply service.

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