UNIVERSITY OF NAIROBI

DEPARTMENT OF EARTH AND CLIMATE SCIENCES

UNIVERSITY OF NAIROBI

URBAN WATER DEMAND, SUPPLY AND HEALTH OUTCOMES IN NAIROBI COUNTY, KENYA

MUTONO NYAMAI

B. Business Information and Technology (Strathmore University, Kenya)

M.Sc. Environment Governance (University of Nairobi, Kenya)

M.Sc. Data Analytics (University of Glasgow, UK)

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Declaration

This thesis is my original work and has not been submitted for award of a degree in any other university.

Mutono Nyamai

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Signature ………………………………… Date: …23/11/2022………………………

Supervisors Declaration

This thesis has been submitted for examination with our approval as university supervisors:

Prof. Henry Mutembei

Department of Clinical Studies & Wangari Maathai Institute

University of Nairobi

Signature: Date: 23/11/2022

Prof. Thumbi Mwangi

Institute of Tropical and Infectious Diseases &

Wangari Maathai Institute, University of Nairobi

&

Paul G Allen School for Global Health, Washington State University

Signature:……………………………… Date……23rd November 2022………

Prof. James Wright

School of Geography and Environment Science

University of Southampton

Signature:……………………………… Date……23rd November 2022………

Dedication

"In trying to explain this linkage, I was inspired by a traditional African tool that has three legs and a basin to sit on. To me the three legs represent three critical pillars of just and stable societies. The first leg stands for democratic space, where rights are respected, whether they are human rights, women's rights, children's rights, or environmental rights. The second represents sustainable and equitable management and resources. And the third stands for cultures of peace that are deliberately cultivated within communities and nations. The basin, or seat, represents society and its prospects for development. Unless all three legs are in place, supporting the seat, no society can thrive. Neither can its citizens develop their skills and creativity. When one leg is missing, the seat is unstable; when two legs are missing, it is impossible to keep any state alive; and when no legs are available, the state is as good as a failed state. No development can take place in such a state either. Instead, conflict ensues."

Prof. Wangari Maathai

To the homo urbanus trying to adapt to the rapidly urbanising environments.

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Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

2SFCA: Two step floating catchment area

ESRI: Environmental Systems Research Institute

GADM: Global Administrative Area Database

GPS: Global Positioning System

JMP: Joint Monitoring Programme for the United Nations Sustainable Goals on Water Supply, Sanitation and Hygiene

KSPA: Kenya Service Provision Assessment

LMIC: Low- and Middle-Income Countries

PHC: Primary Healthcare

SDG: Sustainable Development Goals

SHC: Secondary Healthcare

SSA: Sub-Saharan Africa

THC: Tertiary Healthcare

UHC: Universal Health Coverage

WHO: World Health Organization

Abstract

Introduction: This thesis provides evidence to inform strategies on provision and access of clean drinking water in Nairobi city through provision of data on multi-year patterns on water distribution, association with reported water borne illnesses, forecasting these patterns and disease associations over time and investigate what would be the effect of select mitigation strategies on water sufficiency and public health.

Objectives: The objectives were: 1) To determine the spatio-temporal patterns of the distribution, consumption, and sufficiency of domestic piped water in Nairobi City; 2) To determine the association between water distribution patterns and sufficiency with incidence of cholera in Nairobi City; 3) To model the forecasted risk of water insufficiency levels in Nairobi City by 2025 and determine the optimal mitigation strategies for minimizing this risk.

Materials and methods: To determine the spatio-temporal patterns of domestic water distribution, consumption and sufficiency, data on piped water distribution network, supply and the rationing programs was obtained from Nairobi City Water and Sewerage Company. Data on human population for Nairobi was obtained from WorldPop. To determine the association between water sufficiency and occurrence of waterborne diseases, data on all events of cholera reported in health facilities in Nairobi monthly was obtained from the Kenya Health Information System (KHIS). First, the geographical accessibility to the health facilities and to specified cadres of health professionals for residents in Nairobi City was estimated while accounting for traffic congestion, an important determinant of healthcare utilisation and access. Using cholera incidence data from the health facilities that were accessible to most of the population, spatial cluster analysis was completed to determine cholera hotspots in Nairobi and their association with water sufficiency. Using data on monthly per capita water consumption in residential areas, data on annual population growth rate and non-revenue water for Nairobi City, time series models were used to forecast water demand and estimate the proportion of Nairobi residents that would be at risk of water insufficiency by 2025.

Results: Water sufficiency differed by residential areas, age of neighbourhood and population per itinerary. Compared to residents of low-income areas, those in middle- and high-income areas were four and six times more likely to receive the recommended 1500 litres per capita per month respectively. Analysis of the geographical accessibility to healthcare facilities showed that less than 90% of Nairobi's 4.1 million population were within a 45-minute drive to health facility during peak traffic hours. This increased to >90% during off-peak hours. Compared to secondary healthcare, the data showed a relatively higher optimal ratio of 4.45 healthcare professionals per 1000 people in facilities offering primary and tertiary healthcare during peak and off-peak hours. Cholera hotpots were predominantly in areas receiving less than 1500 litres per person per month, and households located more than 30 meters from a piped sewerage network. Results on forecasting water sufficiency showed that by 2025, monthly water consumption would increase in the middle (47%), middle/low (38%) and high-income areas (21%) whereas a decrease (68%) would be observed in the low-income areas.

Discussion & Recommendations: Findings from this research highlight the need for improved water governance to enhance equity in water supply and access in Nairobi, reduction in the risk of waterborne diseases, and the need for urgent planning and investments to minimize risk of water insufficiency with the growing size of urban population of Nairobi.

Chapter One: General Introduction

1.1 Background

The provision of safe drinking water in urban areas remains one of the fundamental public health interventions in preventing and controlling water-borne diseases, and promoting sustainable development (Rietveld et al., 2016). The importance of this resource is also echoed in target 6.1 of the 2030 United Nations Sustainable Development Goals (SDGs) which aspires to achieve universal and equitable access to adequate and affordable drinking water for all (United Nations, 2015b).

However, two billion people are estimated to lack access to safely managed drinking water (accessible on the premises, available and safe for consumption), with half of this proportion residing in the sub-Saharan African region (United Nations, 2020). Rapid urbanisation and climate variability are thought to be two key factors limiting achievement of the target of water provision for cities in the sub-Saharan African region. By 2050, the urban population is projected to reach 6.7 billion, representing 68% and 66% of the population residing in the global and less developed regions respectively (United Nations Department of Economic and Social Affairs, 2018). Climate variability is endangering the sources and availability of urban water supplies, increasing pressure on available resources (Distefano and Kelly, 2017; Mafuta et al., 2011). The result is inadequate water provision and management which is not commensurate to the rising global demand.

Access to safe water is associated with better health outcomes, livelihood and educational opportunities (Gimelli et al., 2018; Gleick, 1998). However, an estimated 925 million people experience interrupted water supply globally, with a large proportion of urban residents in the global south experiencing intermittent water service (when water is not continuously supplied through a piped water system). This intermittent supply has resulted in urban residents utilising coping mechanisms which include storage of water in their households, collection or purchasing of water from alternative sources, use of water sparingly or recycling water (Majuru et al., 2016), increasing the risk of waterborne illness and exposure to microbial contamination (Bivins et al., 2017; Ercumen et al., 2014; UNICEF and WHO, 2019). Additionally, the unit cost of alternative water sources is higher than piped water, resulting to reduced water consumption and increased risk of inequity, and consequent health concerns (Beard and Mitlin, 2021; WHO, 2020a).

The United Nations' Water Supply and Sanitation Collaboration Council recommends that a household should not spend more than five percent of its income on water and sanitation services (United Nations and Water Supply and Sanitation Collaborative Council, 2011). In low income areas in the global south, studies have reported residents spending up to 20% of their daily wages on water purchases (Monney et al., 2013). Water access in these low income settings is predominantly through water kiosks, where prices are unregulated by the utility companies, resulting to inequalities in cost and mode of water access (Mitlin et al., 2019).

To effectively minimize risk of poor health associated water borne illnesses, water supply to people should be free from contamination, sufficient, easily accessible, reliable, affordable and well governed (Hunter et al., 2010). In the sub-Saharan Africa region, piped water has been categorised as the predominant urban water source that is free from contamination (Vivien and Briceno-Garmendia, 2010). This has also been evidenced in studies assessing the quality of water from different sources(Mutono et al., 2021). In an effort to promote good governance and equitable distribution of the limited water resource, water utility companies implement a predictable water rationing schedule, while aiming to reduce the non-revenue water (water that is lost through leaks, theft or irregular meters) which accounts for a third of the water produced (Beard and Mitlin, 2021b; van den Berg, 2015). In as much as this water schedule has been reported as almost accurate in some regions, there is need to understand whether the quantity and mode of accessing piped water is equitable in urban areas. Additionally, there is need to identify long-term mitigation strategies to have sufficient water provision for domestic purposes and reduce the public health risk of waterborne diseases.

1.2 Statement of Research Problem

Poor water accessibility, quality, quantity, reliability, cost and ease of governance and management have been associated with the increased public health burden of waterborne diseases (Hunter et al., 2010). Growing pressure on the available water resources has been linked to rapid urbanisation and climate change, resulting to wider trends of intermittent piped water supply, poor sanitation and hygiene and inequality in cost and mode of water access (Ganesan et al., 2020; Mutono et al., 2021). The growth of urban infrastructure is not commensurate to the rate of population growth, resulting in inadequate access to resources including water services, health facilities, and housing (Dos Santos et al., 2017; Zhang, 2016).

Goal 3 and Goal 6 of the United Nations Sustainable Development Goals (SDGs) seek to ensure good health and well-being and clean water and sanitation for all by 2030 (United Nations, 2015b). The Joint Monitoring Programme (JMP) routinely measures inequalities in water access and sanitation at household level through to the national scale. However, this data, which is collected via cross-sectional household surveys, makes it difficult to assess the public health burden and changing inequalities over time (Adams et al., 2019).

With an annual population growth rate of 4% and a population of 4.4 million as at 2019, Nairobi is expected to grow into a megacity by 2040 (Bello-Schünemann and Aucoin, 2016; Kenya National Bureau of Statistics, 2019). The comprehensive water distribution network for piped water in Nairobi City was developed in 1985 and since then, users have been added into the system, with no granular analysis on the trends of water distribution and consumption assessed in recent times (Mutono et al., 2021; Mutono et al., 2022). As similar urbanisation trends are expected in urban areas in sub-Saharan Africa, the trends in piped water distribution, inequalities in water access, cost, and quantity, and the association with health is a critical area of study to allow adequate planning and management of the resource. First, the factors that determine water distribution in the city, including the mode of access and per capita monthly volumes of water consumption, and any inequalities in the distribution process, should be understood. Second, the connection between water distribution and health, through the occurrence of waterborne illnesses (such as cholera), as recorded by the health sector needs to be assessed. Furthermore, moderate to long-term forecasting of water demand and sufficiency, and mitigation strategies for water sufficiency in a rapidly urbanising city are important to reduced public health burden associated with waterborne diseases. This thesis aims to understand the spatial and temporal relationships between water supply, distribution, access, and risk of waterborne diseases in Nairobi in order to forecast water demand that will aid in management of this resource. In doing so, this thesis research is concerned with the following questions:

1.2.1 Research questions

1. What are the spatio-temporal patterns of water supply in Nairobi City from 1985 to 2018 and their implications on water sufficiency across the city?
2. What is the association between water sufficiency with incidence of water-borne diseases in Nairobi City?
3. What are the forecasted levels of water sufficiency in relation to population growth, water supply and distribution patterns in Nairobi City by 2025?

1.2.2 General objective

To determine the multi-year water distribution and domestic water consumption patterns in Nairobi City and their association with water borne illness to inform forecasted water sufficiency levels in the population by 2025 and the effect of select mitigation strategies on improvement of water sufficiency and public health.

1.2.3 Specific objectives

a) To determine the spatio-temporal patterns of domestic water distribution, consumption, and sufficiency in Nairobi City from 1985 to 2018

b) To determine the association between water distribution patterns and sufficiency with incidence of cholera in Nairobi City

c) To forecast the water demand for Nairobi City by 2025 and the effect of select mitigation strategies on risk of water insufficiency

1.3 Hypotheses

The guiding hypotheses for this work was that variation in per capita water distribution across Nairobi over time would be associated with inequities in water sufficiency and increased in risk of water borne illnesses.

1.4 Justification

Studies on water in urban settings in sub-Saharan Africa have reported on the quality of water sources (Christenson et al., 2014; Dos Santos et al., 2017), water access patterns (Nayebare et al., 2014), water intermittency (Adane et al., 2017), and restructuring of water infrastructure to meet the needs of the dynamic population in urban areas in this region (Nilsson, 2016). However, there have been limited studies on the water distribution patterns in cities in sub-Saharan Africa and the per capita daily water consumption even though water access and adequacy have been associated with health (WHO, 2020a). Understanding the intra-urban water distribution patterns in these developing regions is important for planning and achieving goal 3 and goal 6 of the United Nations Sustainable Development Goals of ensuring access to water and sanitation and good health and wellbeing for all by 2030 (United Nations, 2015b).

Chapter Two: Literature Review

2.0 Introduction

From 1960, urban sub-Saharan Africa (SSA) has been experiencing annual population growth of more than 3.5%, which is higher than the world average and the rate observed in high-income regions (World Bank, 2019). However, the growth of urban infrastructure has been slower, leading to populations without access to adequate resources including water, increase in informal settlements and urban poverty (Zhang, 2016). These challenges of urbanisation are especially prevalent in SSA (Dos Santos et al., 2017). By 2025, it is estimated that globally, one in every two people will be living in water stressed areas and this will increase the challenge of water supply (WHO, 2020b).

2.1 Urban Water Sufficiency

As of 2017, only half of the population residing in urban areas in SSA had access to safely managed drinking water, meaning piped, borehole, protected well or springs, rainwater, or packaged water free from contamination, which was available when needed and accessible on the premises (UNICEF and WHO, 2019). It has been reported that more than half (53%) of the water sources in Africa have faecal contamination, leading to an increased risk of diarrheal diseases (Bain et al., 2014). The Africa Infrastructure Country Diagnostic report by the World Bank categorised piped water as the only major source of improved water in urban areas in SSA, which in 2017, was only accessible to 152 million people (15%) in this region (UNICEF and WHO, 2019; World Bank and Infrastructure Consortium for Africa, 2010). In addition, Kenya is geared towards ensuring piped water is the main source of water in urban areas by 2030 (Government of the Republic of Kenya, 2013).

In SSA, piped water is mainly supplied by the water utility companies, and accessed by households through inhouse connection, shared tap at compound or a public tap/water kiosk (Adane et al., 2017; Dos Santos et al., 2015; Ubosi, 2018; Winter et al., 2019). Insufficient piped water supply has been a common trend reported in urban areas in this region where residents implement coping mechanisms which include storing water in their households and/or use of alternative sources of water which include wells, springs, trucks or vendors (Barzilay et al., 2011; Dos Santos et al., 2015; Essayagh et al., 2019; Sakijege, 2019). Studies by Oguntoke et., al and Ako et., al have both reported that 96% of the study population relied on alternative sources as the major sources of drinking water (Ako et al., 2009; Oguntoke et al., 2009). The unit cost of these alternative sources of water is relatively higher than the cost of water supplied by utility companies (Abaje et al., 2009; Sakijege, 2019; Stoler et al., 2012a; Traoré et al., 2013).

Water insufficiency is predominantly driven by increase in population, urbanisation, water scarcity and climate change (Chakava et al., 2014; Distefano and Kelly, 2017; Mafuta et al., 2011; WHO, 2020b). Positive correlations between urbanisation and inequality during provision of basic services has been reported (Zhang, 2016). Inequality has been observed in water accessibility, cost and quantities of water consumption where low-income households mainly access water through water kiosks, consume less than 20 litres per person per day yet end up paying up to nine times the unit cost of water (Machdar et al., 2013). The cost of water in these low income areas is not regulated by utility companies, as the public taps are owned by individuals (Traoré et al., 2013). In addition, water connection and rationing plans do not prioritise on these low-income areas which are the predominant epicentres of waterborne disease outbreaks (Sakijege, 2019).

2.2 Urban Water Quality

The Joint Monitoring Programme (JMP) on the world indicators of the United Nations Sustainable Development Goals (SDGs) on drinking water, sanitation and hygiene list boreholes and rainwater among the improved water sources (UNICEF and WHO, 2019). However, studies that have assessed the quality of these water sources have reported presence of faecal coliforms in others sources besides piped water (Barzilay et al., 2011; Dégbey et al., 2008; Dunne et al., 2001; Oguntoke et al., 2009; Sakijege, 2019). These study findings support the Africa Infrastructure County Diagnostic report which listed piped water as the only source of improved water in this region (Banerjee and Morella, 2011). However, this resource is only accessible to nearly half of the urban residents, who in addition experience intermittent supply (Mitlin et al., 2019). To cope with this unreliable supply, residents supplement their water needs including through maintaining water storing reservoirs in their households or seeking alternative sources of water (Majuru et al., 2016). High income residents invest in large storage tanks which ensure they enjoy adequate water consumption even during periods of irregular water supply (Ledant, 2013). On the other hand, the low income earners, who account for 61% of the population in Africa rely on unimproved water storage, increasing their risk to water contamination (African Development Bank, 2011; Amrose et al., 2015).

2.3 Water and Health

In 2016, more than half a billion deaths in SSA were attributed to diarrheal diseases, with water contamination identified as one of the leading risk factors (Troeger et al., 2018). *Escherichia coli*, *Cryptosporidium* spp., *Aeromonas* spp., *Shigella* spp., and

Entamoeba have been reported as major pathogens leading to increased risk of death in children below one year with moderate-to-severe diarrhoea in low and middle income countries (Levine et al., 2020). This high burden has led to the high prioritisation of waterborne diseases and syndromes, with several of them (cholera, diarrheal diseases, typhoid fever) listed in the Integrated Disease Surveillance and Response (IDSR) Strategies in use in most African countries (Fall et al., 2019). With this surveillance system, whose custodian is the Ministry of Health, health facilities are meant to key in monthly reports on cases of notifiable diseases (Manya et al., 2012).

Several studies have reported high prevalence of waterborne diseases and syndromes (cholera, cryptosporidium, typhoid, amoebiasis, diarrhoea, dysentery, giardiasis and rotavirus) in urban areas in SSA (Akinbo et al., 2010; Endris et al., 2019; Kone-Coulibaly et al., 2010; Oguntoke et al., 2009; Sakijege, 2019; Ubosi, 2018). Several factors including consumption of unclean water, intermittent water supply, daily per capita water consumption of less than 20 litres, low income, travel time of more than thirty minutes to fetch water from source and poor water storage have been reported to be significantly associated with increased risk of these waterborne diseases (Adane et al., 2017; Dos Santos et al., 2015; Endris et al., 2019; Kone-Coulibaly et al., 2010; Muti et al., 2014; Winter et al., 2019; Yilgwan et al., 2010).

2.4 Water Governance and Management

Urban water insufficiency and the relationship to waterborne diseases has been directly or indirectly linked to several of the international agreements, which include United Nations SDGs that focus on ensuring sustainable cities and communities by 2030 (goal 11), accessibility of clean water to all (goal 6), good health and well-being to all (goal

3) and reducing inequalities (goal 10) (United Nations, 2015b). Additionally, the African Union Agenda 2063 aspires to have an African continent that is based on inclusive growth and sustainable development (African Union, 2015).

In Kenya, the Constitution of Kenya which was promulgated in 2010, acknowledges access to clean and safe water as a right (Article 43 (1)(d)), and obligates the State to ensure programmes are designed to ensure reasonable access to water among minorities, and marginalized groups (Article 56(e)) (Constitution of Kenya, 2010). To ensure the water sector aligns to the objective of the constitution, the Kenya Water Act was gazetted in 2016 (Kenya Water Act, 2016). This act ensures that the utility companies have:

(i) Water distribution that complements the water demand patterns

(ii) Equity in water distribution

To facilitate planning and management of water, while adhering to the Constitution of Kenya and the Water Act, the National Water Master Plan 2030 was developed with the main objective of ensuring sustainability of water consumption and county water resources up to 2050 (Government of the Republic of Kenya, 2013). The masterplan is working towards ensuring all residents in urban areas dominantly use piped water, with a per capita monthly water consumption of 4380 litres for domestic purposes, and a non-revenue water target of 20% by 2030 (Government of the Republic of Kenya, 2013). In addition, the 2019 guidelines on water vending which are overseen by the Water Service Regulatory Board aim to ensure vended water is of quality, and cost effective through water tariffs to ensure increased consumption of safe drinking water (WASREB, 2019).

The water masterplan per capita monthly water consumption target is in line with the recommended target of at least 1,500 litres of safe drinking water per person per month which enhances water sufficiency and minimal risk of waterborne diseases (WHO, 2020a). To achieve this target, good governance and management is required both during the distribution and planning process of this resource (Hunter et al., 2010).

Previous studies have focused on water quality, vulnerability of the resource and the reallocation of water from rural to urban regions in SSA (Bain et al., 2014; Garrick et al., 2019; Plummer et al., 2012; Thomas et al., 2020; Wright et al., 2004). Other studies have focused on the environment determinants of waterborne disease outbreaks, the link between waterborne diseases and water resource development in Africa and climate change globally (Levy et al., 2016; Rebaudet et al., 2013; Steinmann et al., 2006). However, few studies are available on insufficiencies of piped water consumption in urban areas at a granular scale in sub-Saharan Africa, which by 2050 will accommodate more than two thirds of the population (UN-HABITAT, 2016). Additionally, the association with waterborne diseases and syndromes in the African continent, which has a disproportionate burden of waterborne diseases and syndromes is also scarce (Ajero et al., 2008; Aldeyarbi et al., 2016; Endris et al., 2019; Sanchez-Padilla et al., 2009). This study addresses this gap on knowledge on the spatio-temporal patterns of water distribution on a granular scale, and the association with waterborne diseases in African cities. This is done by assessing water distribution and consumption patterns in Nairobi city over multiple years using small area statistics called itineraries (with an average population of 700 persons each), and the association between water sufficiency and a water-borne health outcome (cholera). Further, the study forecasts water demand up to 2025, and determines the effect select mitigation measures would have on proportion of the population that would be water insufficient by 2025.

2.1 Theoretical Framework

The rate of infrastructure growth in Nairobi City is slower than the rate of urbanization and population growth resulting in water insufficiency for some of the Nairobi city residents. This is supported by the catastrophe theory which looks at a state of equilibrium required by the external and internal drivers of a resource (Xiao-jun et al., 2014). The external drivers of water include population growth, climate change among others while the internal drivers include infrastructure, non-revenue water and regulatory frameworks. The rate of infrastructure growth should complement the rapidly urbanisation population to ensure an equilibrium system. The infrastructure should also ensure water losses are addressed to enhanced sustainable water supply.

The amenity based theory also supports this study as it states that the socio-economic determinants are the main drivers of amenities, where the residents in higher income areas have better access to basic amenities and better infrastructure (Brueckner et al., 1999). This is likely to increase inequalities in a city, resulting to people in lower income regions not adequately served with resources such as water, leading to a reliance on alternative sources to complement the insufficient water supply. The alternative sources of water may be contaminated leading to increase in health consequences in Nairobi City. The amenity-based theory has been able to explain the inequalities experienced in multiple cities and this study aimed to test this theory (Brueckner et al., 1999).

By applying the two theories to this study, it can be argued that water provision and access to clean water services essentially ought to provide a vital link to fundamental stainability nexus between biophysical limitations and human demand (UNEP, 2019). The studies in this research thesis tried to create understanding on the relationship between supply and demand for water resources in urban areas while accounting for supply side of service resources and the demand side for the involved resource service beneficiaries (FAO, 2020). An understanding of the demand for particular resource service from different group of beneficiaries in different urban landscapes is dependent upon studying the factors that affect sustainable supply and utilisation of the resource; spatio-temporal distribution patterns, policy and regulatory frameworks, and external and internal factors affecting methods of obtaining the water resource services (Yahdjian et al., 2015).

2.6 Conceptual Framework

Water quality, quantity, reliability, cost, access, governance and management have been proposed as key factors that determine whether a water supply is able to effectively enhance good health (Hunter et al., 2010). Rapid urbanisation and climate change have been increasing the pressure on the available water sources, contributing to water insufficiency in cities in sub-Saharan Africa (SSA) (Mitlin et al., 2019). In addition, the growth of the water infrastructure in this region is not commensurate to the rate of urbanisation, resulting to increased intermittent water supply, and high levels of non-revenue water (van den Berg, 2015). To complement their water needs, residents in urban areas in SSA either collect or purchase water from alternative sources, use water sparingly, or store water in their households (Majuru et al., 2016). These alternative sources of water have been reported to be contaminated with faecal matter, increasing the public health burden associated with waterborne diseases in the region (Bain et al., 2014). Outbreaks and cases of waterborne diseases have increased in magnitude and frequency in the last few years, with water sufficiency and quality being reported as some of the risk factors (Kim et al., 2019; Mutono et al., 2021).

The WHO recommended per capita monthly safe water consumption to ensure low levels of health concern is least 1500 litres (WHO, 2020a). With piped water being categorized as the only safe water source in urban areas in SSA, there is need to ensure good governance and management of this resource which has been reported to experience inequality in access, cost, and quantity (Banerjee and Morella, 2011; Mutono et al., 2021). Utility companies have implemented equitable distribution of piped water through the water rationing schedules (Beard and Mitlin, 2021b). Even though these schedules have been reliable, the water intermittency needs to complement the needs and storage capacity of the households, where the residents in low income areas use poor water storage practices, increasing the risk of waterborne diseases (Mutono et al., 2021). To ensure sustainable governance and management of water, the utility companies ought to identify the challenges in the existing water distribution process in a rapidly urbanizing cities, understand the level of health concern resulting from the current distribution, and implement a water mitigation strategy for the future to ensure the public health burden on waterborne diseases is reduced. The governance and management of water should ensure there are low levels of health concern. The water distribution patterns in these rapidly urbanizing cities and their links to waterborne diseases should be understood. Furthermore, a forecasting of the water demand in these cities is required to enable sustainable governance and management of the limited resource for improved health outcomes. Water forecasting and a water insufficiency mitigation plan for the city is required to ensure the utility company plans for the water needs, while safeguarding residents from the risk of waterborne diseases. Figure 1 shows the study conceptual framework.

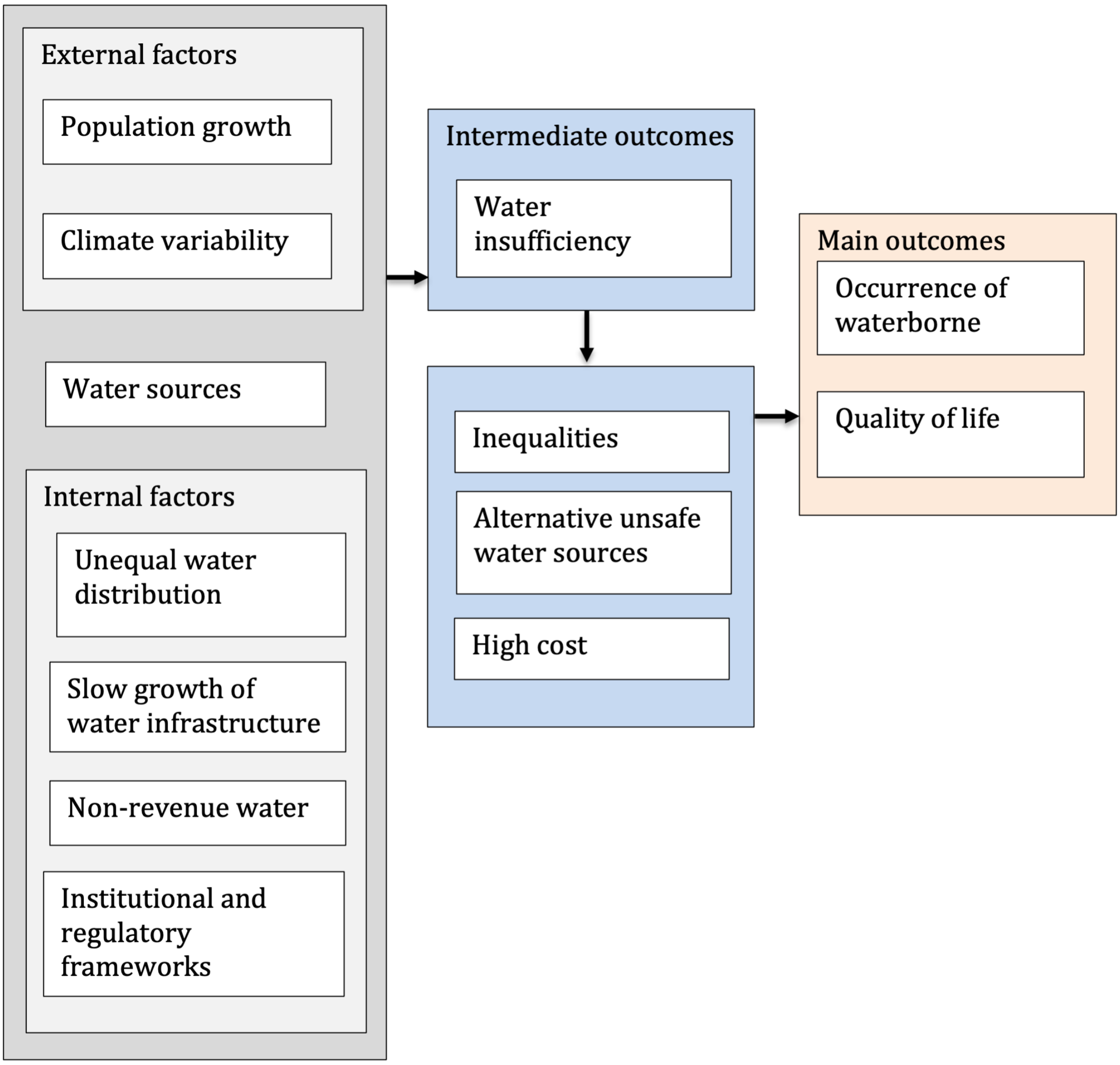

Figure 1: Conceptual framework summarising the link between water and health, and the role of governance and management

Chapter Three: Materials and Methods

(Part of this chapter has been published in the Africa Academy of Sciences Open Research Journal: DOI- 10.12688/aasopenres.13225.1)

3.1 Study Area

The study focused on Nairobi County, which is the capital city of Kenya and the most populous county in Kenya with a population of 4.1 million and a population density of 6,247 people per km^2 (Kenya National Bureau of Statistics, 2019). Nairobi County is one of the cities in sub Saharan Africa that will experience a growth rate of 2.6% and a population estimate of 7 million people by 2030 (World Bank, 2019). With the increased population, water stress will be drastic in Nairobi (JICA, 2013).

The choice of Nairobi County for this study allowed for the calculation of urban water demand in a rapidly urbanising city and assessing how water demand and supply would correlate with water borne diseases, with a focus on cholera, which is epidemic prone. Within Nairobi County, the study targeted households that were supplied and directly billed by the Nairobi Water and Sewerage Company monthly.

3.1.1 Climatic Conditions

Temperatures range from a low of 10°C to a high of 29° C. The long rains season falls between March and May with an average rainfall of 899 millimetres while the short rains season falls between October and December with an average annual rainfall of 638 millimetres. The mean annual rainfall for the county is 786.5 millimetres (Thorn et al., 2015).

3.2 Study Design

The study first assessed how the relationship between waterborne diseases and water sufficiency had been studied in urban Africa. This was followed by assessing the spatio-temporal patterns of piped water supply, access, and consumption, and how these was associated with health outcomes. Finally, a water forecasting was conducted to understand the water consumption patterns by 2025 and what mitigation strategies would be required to ensure the population at risk of water insufficiency would be reduced to the bare minimum. The specific methodology used for each objective is discussed in the succeeding chapters.

3.2.1 Selection of Itineraries and Health Facilities

Nairobi Water and Sewerage Company has divided Nairobi into itineraries based on the billing and metering system. Nairobi County is divided into over 2500 itineraries, with each itinerary having a selected number of customers who can be residential houses or commercial areas. The selection of the itineraries to be included in this study followed the stages below:

i. Selection of itineraries: the selection of itineraries to be included in the study was determined by one main operational consideration: the functionality of the itinerary by the volumes of water supplied to that itinerary and the number of customers in the itineraries. The study focused on:

    a. Itineraries that were under residential areas. The study mainly focused on water supply and demand in residential areas hence itineraries that fell in designated commercial areas were not included in the study.

    b. Itineraries that had geographical coordinates under the itineraries shapefile used by Nairobi City Water and Sewerage Company. This allowed us to look at both spatial and temporal patterns of water demand and supply in these itineraries

c. Itineraries with non-zero customers and non-zero volumes of water supplied per month

ii. Selection of health facilities: All health facilities that were under the jurisprudence of Nairobi County and registered by the Ministry of Health were included in the healthcare accessibility study. All clinically confirmed cholera cases from primary health facilities and reported through the Kenya Health Information System under the Ministry of Health between 2015 to 2021 was included in the study.

3.2.2 Inclusion Criteria

Only itineraries that met the following study criteria were included in the study:

- Existing customers in the itinerary
- Itineraries that supplied water to residential areas
- Operational itineraries with monthly volumes of water supplied to that itinerary
- Itineraries that had geo-coordinates

Only health facilities that met the following study criteria were included in the study:

- Registered under the Ministry of Health
- Within the jurisprudence of Nairobi County
- Reported data in the KHIS system

3.2.3 Exclusion Criteria

Itineraries excluded in the study had the following criteria:

- Non existing or zero customers in the itinerary
- Itineraries that supplied water to commercial areas

- Non-operational itineraries that had no monthly volumes of water supplied to them

Health facilities that were excluded in the study were:

- Not registered under the Ministry of Health
- Not reporting data under the KHIS system

3.2.2 Ethical Considerations

The study was registered under the Kenya National Commission for Science, Technology, and Innovation (NACOSTI). Permission was also sought from Nairobi Water and Sewerage Company and the Ministry of Health. As the study was using aggregated de-identified data, ethical approval was not required. However, national laws and regulations, including those of NACOSTI, were followed.

3.2.3 Participant Data Protection

The data was only accessible to the study investigators. Electronic copies of the data were password protected. No individual identifiers were collected in data from the health facility and from Nairobi Water and Sewerage Company.

3.3 Data Collection Tools and Research Materials

Data from Nairobi City Water and Sewerage Company was collected from their databases through carrying out select/ filters of the itineraries under the study. The data was stored in Microsoft Excel.

The data from the hospitals was collected from the Kenya Health Information Systems database and stored in Microsoft Excel.

Data analysis for this study was mainly conducted using the R statistical computing environment (R Core Team, 2017b). A detailed research design and analysis for each objective is provided in the following chapters.

3.4 Scoping Review on the Nexus between Improved Water Supply and Water-Borne Diseases in Urban Areas in Africa

3.4.1 Introduction

Sub-Saharan Africa (SSA) has experienced the highest annual urban population growth rate (more than 3.5%) in the world (World Bank, 2019). However, the growth of urban infrastructure has been slower, leading to populations without access to adequate resources including water services, health facilities, and housing (Dos Santos et al., 2017; Zhang, 2016).

Globally, it is estimated that one in every two people will be living in water stressed areas by 2025 increasing the challenge of water supply (WHO, 2020b). As of 2017, only half of the population residing in urban areas in SSA had access to improved water sources which included piped, boreholes, protected wells or springs, rainwater or packaged water (UNICEF and WHO, 2017). However, going by The World Bank categorisation of piped water as the only major source of improved water in urban areas in SSA (Vivien and Briceno-Garmendia, 2010), only 56% (230 million) of the population residing in urban areas in this region have access to clean water (UNICEF and WHO, 2019).

Here, a scoping review was conducted to assess the link between sufficient access to piped water supply and waterborne diseases and syndromes in African cities. Specifically, the following questions were answered: i) How has the relationship between waterborne diseases and piped water sufficiency been studied in Africa? ii)

Are there under-utilised study designs, under-studied metrics of water sufficiency or under-studied syndromes or waterborne diseases?

3.4.2. Methods

3.4.2.1 Literature Search Methods

This scoping review was conducted following the Joanna Briggs Institute methodology guidance for scoping reviews (M. Peters et al., 2020) and the preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension guidelines for conducting scoping reviews (Khalil et al., 2016; Tricco et al., 2016). Briefly, this approach involves: i) conducting a systematic literature search to identify articles that meet the inclusion criteria, ii) assessing the relevance of the articles to the study question(s), iii) assessment of the full text articles iv) data extraction and synthesis. The scoping review protocol for this study is published and available (Mutono et al., 2020). The 32 articles selected for the literature review section in chapter two were also used for this chapter.

3.4.2.2 Data Extraction, Synthesis, and Presentation

Variables on author(s), study period, source of funding, geographical scope, study design, population inclusion criteria, sample size and statistical methodology used, and whether the study investigated a disease outbreak were extracted from the studies.

To understand piped water access and quality reported by the studies, information on the nature of the piped water supply, mode of accessing this piped water, measurement of the unit cost of water, the per capita daily water consumption, proportion of the population without access to piped water and water quality indicators from water samples collected for testing was extracted. The reported coping mechanisms employed to supplement water needs were also extracted. Information on the health outcomes studied and how diagnoses was made (self-reported, clinically diagnosed or culture confirmed) was also extracted from the articles. Table 1 provides a list of the variables extracted from the articles during the screening process.

Table 1: Description of variables that were extracted from the articles during full-text screening

Variable	Description/ Example
Study design	
Study period	Year(s)
Geographical scope of the study	City/ cities where the study was conducted
Source of funding	Government sponsored/ philanthropic foundation/ research institute/ not sponsored
Study design	Cross-sectional individual/ cross-sectional ecological/ case control/ case series/ cohort
Population inclusion criteria	Households/ women/children/confirmed cases etc.
Sample size (people)	Number of respondents / households
Sample size	Number of water/ stool/ soil samples for testing
Outbreak investigation	Yes/No
Statistical methodology used	
Bivariate methods	Chi-square tests, Fischer tests etc.
Multivariate methods and	Linear models, logistic models etc. and confounders/ alternative transmission pathways / effect modifiers assessed
Indicators of piped water sufficiency	
Nature of piped water supply	Continuous/ scheduled interruptions/unpredictable interruptions
Mode of water access	Inhouse piped connection, shared tap at yard, public tap/water kiosk
Unit cost of water reported	Yes/No
Measurement of per capita daily water consumption	Yes/No
Proportion of population without access to piped water	Metric
Water quality indicators from water samples collected for testing	
- Faecal indicator organism test	e.g., total coliforms, Escherichia coli
- Dosage test for chlorine	e.g., Free chlorine residual test
- Pathogen tested for	e.g., *Klebsiella pneumoniae*, *Salmonella* spp., *Shigella* spp., *Pseudomonas aeruginosa*
- Consumer reported organoleptic water characteristics	e.g., smell, taste, visual appearance

- Laboratory or organoleptic field tests	e.g., electroconductivity, pH and turbidity
Coping mechanism employed to supplement water needs	
- Use of storage tanks	Yes/No
- Storage of water in households in containers, bottles etc.	Yes/No
- Installation of pumps for piped water where water pressure is low	Yes/No
- Collecting water from rivers/streams, shallow wells, rainwater	Yes/No
- Drilling of wells/boreholes	Yes/No
- Installation of hand pumps/electric pumps for groundwater	Yes/No
- Water treatment	Yes/No
- Purchasing water from vendors	Yes/No
- Purchasing water from neighbours	Yes/No
- Water recycling	Yes/No
- Illegal water connections	Yes/No
Indicators of health	
- Cholera	Self-reported/Clinically diagnosed/ laboratory confirmed
- Typhoid	Self-reported/Clinically diagnosed/ laboratory confirmed
- Amoebiasis	Self-reported/Clinically diagnosed/ laboratory confirmed
- Cyclosporiasis	Self-reported/Clinically diagnosed/ laboratory confirmed
- Giardiasis	Self-reported/Clinically diagnosed/ laboratory confirmed
- Dysentery	Self-reported/Clinically diagnosed/ laboratory confirmed
- Diarrhoea	Self-reported/Clinically diagnosed/ laboratory confirmed
- Gastroenteritis	Self-reported/Clinically diagnosed/ laboratory confirmed
- Cryptosporidium	Self-reported/Clinically diagnosed/ laboratory confirmed
- Rotavirus	Self-reported/Clinically diagnosed/ laboratory confirmed

3.4.2.3 Connectedness of the Study Designs of the Associations between Water Sufficiency and Health Outcomes

To understand the connectedness of the different study designs with the health outcomes and water sufficiency metrics and water quality, the principal component techniques were used (Collins et al., 2020). The main categories of the study designs employed in the selected publications were evaluated together with the health outcomes (self-reported, clinically or culture confirmed) and a binary coding of assessment of water quality. The water sufficiency metrics were coded into either water access (mode of access, proportion with access, time/distance to water points) or water quantity (scheduled/ unscheduled interruptions, litres per person per day) categories. Multiple factor analysis was carried out by grouping the study designs, health outcomes, water sufficiency metrics and whether water quality was assessed. Contributions of the first two axes were observed and the combinations of the variables that were connected, understudied and the outliers were assessed. The analysis was carried out using the FactomineR package in the statistical software R (Lê et al., 2008; R Core Team, 2017a).

3.4.3. Results

3.4.3.1 Characteristics of the Publications

A total of 32 articles that assessed the association of water sufficiency in urban areas and waterborne diseases and syndromes in SSA were published between 1998 and 2019. Seven of the articles (22%) were conducted in informal settlements (Adane et al., 2017; Blanton et al., 2015; Kone-Coulibaly et al., 2010; Machdar et al., 2013; Sow et al., 1999; Stoler et al., 2012a; Winter et al., 2019; Yilgwan et al., 2010). Nearly half the studies did not report the source of funding, with government and philanthropies supporting most of the studies that provided the information (Table 2).

Table 2: Characteristics of the 32 studies included in the scoping review

Characteristic	No. of studies (% of included studies)	References
Study period†		
≤ 2005	12 (38%)	(Ako et al., 2009; Barzilay et al., 2011; Dunne et al., 2001; Julvez et al., 1998; Nkhuwa, 2003; Oguntoke et al., 2009; P.S. et al., 1999; Usman et al., 2005; Yilgwan et al., 2010; Yongsi, 2010)
2006 - 2012	14 (43%)	(Abaje et al., 2009; Akinbo et al., 2010; Ako et al., 2009; Baker et al., 2013; Blanton et al., 2015; Degbey et al., 2011; Dorice et al., 2008; Dos Santos et al., 2015; Kone-Coulibaly et al., 2010; Machdar et al., 2013; Muti et al., 2014; Schaetti et al., 2013; Stoler et al., 2012a; Traoré et al., 2013; Von Nguyen et al., 2014; Yongsi, 2010)
≥ 2013	8 (25%)	(Adane et al., 2017; Endris et al., 2019; Essayagh et al., 2019; Navab-Daneshmand et al., 2018; Sakijege, 2019; Sinyange et al., 2018; Ubosi, 2018; Winter, Dzombo, et al., 2019)
Source of funding		
Not reported	15 (47%)	(Abaje et al., 2009; Ako et al., 2009; Blanton et al., 2015; Dunne et al., 2001; Endris et al., 2019; Essayagh et al., 2019; Kone-Coulibaly et al., 2010; Muti et al., 2014; Nkhuwa, 2003; Oguntoke et al., 2009; Sinyange et al., 2018; Sow et al., 1999; Ubosi, 2018; Usman et al., 2005; Yilgwan et al., 2010)
Government departments/ agencies	6 (19%)	(Akinbo et al., 2010; Barzilay et al., 2011; Machdar et al., 2013; Stoler et al., 2012a; Von Nguyen et al., 2014; S. Winter, Dzombo, et al., 2019)
Philanthropic foundations	5 (16%)	(Baker et al., 2013; Dorice et al., 2008; Navab-Daneshmand et al., 2018; Schaetti et al., 2013; Traoré et al., 2013)
Research Institutes	4 (13%)	(Adane et al., 2017; Dos Santos et al., 2015; Julvez et al., 1998; Yongsi, 2010)
Not sponsored	2 (6%)	(Degbey et al., 2011; Sakijege, 2019)

Study design		
Cross- sectional individual-level	16 (50%)	(Abaje et al., 2009; Blanton et al., 2015; Dorice et al., 2008; Dos Santos et al., 2015; Julvez et al., 1998; Machdar et al., 2013; Navab-Daneshmand et al., 2018; Sakijege, 2019; Schaetti et al., 2013; Stoler et al., 2012a; Ubosi, 2018; Winter et al., 2019; Yilgwan et al., 2010; Yongsi, 2010)
Case-control	9 (28%)	(Adane et al., 2017; Akinbo et al., 2010; Baker et al., 2013; Dunne et al., 2001; Endris et al., 2019; Kone-Coulibaly et al., 2010; Muti et al., 2014; Von Nguyen et al., 2014)
Cross-sectional ecological	7 (22%)	(Ako et al., 2009; Degbey et al., 2011; Nkhuwa, 2003; P.S. et al., 1999; Traoré et al., 2013; Usman et al., 2005)
Cohort	2 (6%)	(Barzilay et al., 2011; Essayagh et al., 2019)
Cross-sectional ecological and individual level	1 (3%)	(Oguntoke et al., 2009)
Cross-sectional individual-level and case control	1 (3%)	(Sinyange et al., 2018)
Population inclusion criteria†		
Households/ respondents	17 (53%)	(Abaje et al., 2009; Ako et al., 2009; Blanton et al., 2015; Dorice et al., 2008; Endris et al., 2019; Julvez et al., 1998; Kone-Coulibaly et al., 2010; Machdar et al., 2013; Muti et al., 2014; Navab-Daneshmand et al., 2018; Oguntoke et al., 2009; Sakijege, 2019; Schaetti et al., 2013; Sinyange et al., 2018; Traoré et al., 2013; Von Nguyen et al., 2014; Yilgwan et al., 2010)
Confirmed cases/ people visiting health facilities for treatment of waterborne diseases	6 (19%)	(Degbey et al., 2011; Essayagh et al., 2019; Nkhuwa, 2003; Oguntoke et al., 2009; Sow et al., 1999; Usman et al., 2005)
Children/ infants	6 (19%)	(Adane et al., 2017; Baker et al., 2013; Dos Santos et al., 2015; Julvez et al., 1998; Stoler et al., 2012a; Yongsi, 2010)
Women or mothers of infants	3 (9%)	(Stoler et al., 2012a; Ubosi, 2018; Winter et al., 2019)
HIV positive persons	3 (9%)	(Akinbo et al., 2010; Barzilay et al., 2011; Dunne et al., 2001)
Study population sample size		
≤100	2 (6%)	(Blanton et al., 2015; Sakijege, 2019)

101-200	7 (22%)	(Degbey et al., 2011; Dunne et al., 2001; Machdar et al., 2013; Navab-Daneshmand et al., 2018; P.S. et al., 1999; Von Nguyen et al., 2014; Yilgwan et al., 2010)
201-300	7 (22%)	(Abaje et al., 2009; Ako et al., 2009; Barzilay et al., 2011; Endris et al., 2019; Kone-Coulibaly et al., 2010; Muti et al., 2014; Ubosi, 2018)
301-400	4 (13%)	(Essayagh et al., 2019; Julvez et al., 1998; Oguntoke et al., 2009; Schaetti et al., 2013)
400-500	1 (3%)	(Akinbo et al., 2010)
>500	11 (34%)	(Adane et al., 2017; Baker et al., 2013; Dorice et al., 2008; Stéphanie Dos Santos et al., 2015; Nkhuwa, 2003; Sinyange et al., 2018; Stoler et al., 2012a; Traoré et al., 2013; Usman et al., 2005; Winter, et al., 2019; Yongsi, 2010)
Study investigating an outbreak	10 (31%)	(Blanton et al., 2015; Endris et al., 2019; Essayagh et al., 2019; Kone-Coulibaly et al., 2010; Muti et al., 2014; P.S. et al., 1999; Schaetti et al., 2013; Sinyange et al., 2018; Usman et al., 2005; Von Nguyen et al., 2014)
Statistical methodologies used (n=25) †		
Bivariate methods (chi-square tests, Fischer tests etc.)	17 (68%)	(Abaje et al., 2009; Akinbo et al., 2010; Baker et al., 2013; Barzilay et al., 2011; Blanton et al., 2015; Degbey et al., 2011; Dorice et al., 2008; Endris et al., 2019; Essayagh et al., 2019; Navab-Daneshmand et al., 2018; Oguntoke et al., 2009; Schaetti et al., 2013; Stoler et al., 2012a; Traoré et al., 2013; Ubosi, 2018; Von Nguyen et al., 2014; Winter, et al., 2019; Yongsi, 2010)
Multivariate methods (Linear models, logistic models etc.)	12 (48%)	(Adane et al., 2017; Baker et al., 2013; S. Dos Santos et al., 2015; Kone-Coulibaly et al., 2010; Muti et al., 2014; Navab-Daneshmand et al., 2018; Oguntoke et al., 2009; Sinyange et al., 2018; Stoler et al., 2012a; Von Nguyen et al., 2014; S. Winter, Dzombo, et al., 2019; Yilgwan et al., 2010)
Nature of piped water supply†		
Proportion with access to piped water	23 (72%)	(Abaje et al., 2009; Akinbo et al., 2010; Ako et al., 2009; Baker et al., 2013; Barzilay et al., 2011; Blanton

		et al., 2015; Dorice et al., 2008; Dos Santos et al., 2015; Dunne et al., 2001; Essayagh et al., 2019; Kone-Coulibaly et al., 2010; Machdar et al., 2013; Navab-Daneshmand et al., 2018; Nkhuwa, 2003; Oguntoke et al., 2009; P.S. et al., 1999; Stoler et al., 2012a; Traoré et al., 2013; Ubosi, 2018; Von Nguyen et al., 2014; S. Winter, Dzombo, et al., 2019; Yilgwan et al., 2010; Yongsi, 2010)
Water interruptions (scheduled/unpredictable)	8 (25%)	(Abaje et al., 2009; Adane et al., 2017; Blanton et al., 2015; Dunne et al., 2001; Kone-Coulibaly et al., 2010; Machdar et al., 2013; Stoler et al., 2012a; Von Nguyen et al., 2014)
Per capita daily water availability	5 (16%)	(Abaje et al., 2009; Adane et al., 2017; Dos Santos et al., 2015; Julvez et al., 1998; Traoré et al., 2013)
Cost / affordability of water metric	4 (13%)	(Abaje et al., 2009; Sakijege, 2019; Stoler et al., 2012a; Traoré et al., 2013)
Time used/distance to water point	3 (9%)	(Abaje et al., 2009; Baker et al., 2013; Dos Santos et al., 2015)
Samples collected†		
Water	19 (59%)	(Adane et al., 2017; Ako et al., 2009; Baker et al., 2013; Barzilay et al., 2011; Blanton et al., 2015; Degbey et al., 2011; Dunne et al., 2001; Julvez et al., 1998; Machdar et al., 2013; Muti et al., 2014; Navab-Daneshmand et al., 2018; Nkhuwa, 2003; Oguntoke et al., 2009; Sakijege, 2019; Sinyange et al., 2018; Traoré et al., 2013; Usman et al., 2005; Von Nguyen et al., 2014; Yongsi, 2010)
Stool	5 (16%)	(Akinbo et al., 2010; Endris et al., 2019; Muti et al., 2014; Sinyange et al., 2018; Von Nguyen et al., 2014)
Soil	1 (3%)	(Navab-Daneshmand et al., 2018)
Hand rinse	1 (3%)	(Navab-Daneshmand et al., 2018)
Water quality indicators (n=19)†		
Faecal indicator organism test	17 (89%)	(Adane et al., 2017; Ako et al., 2009; Baker et al., 2013; Blanton et al., 2015; Degbey et al., 2011; Dunne et al., 2001; Julvez et al., 1998; Machdar et al., 2013; Muti et al., 2014; Navab-Daneshmand et al., 2018; Nkhuwa, 2003;

		Oguntoke et al., 2009; Sakijege, 2019; Sinyange et al., 2018; Traoré et al., 2013; Usman et al., 2005; Yongsi, 2010)
Free chlorine residual test	7 (37%)	(Ako et al., 2009; Baker et al., 2013; Blanton et al., 2015; Dunne et al., 2001; Muti et al., 2014; Nkhuwa, 2003; Sinyange et al., 2018)
Laboratory/field tests organoleptic water characteristics	5 (26%)	(Ako et al., 2009; Barzilay et al., 2011; Nkhuwa, 2003; Sakijege, 2019; Von Nguyen et al., 2014)
Pathogen tests	5 (26%)	(Degbey et al., 2011; Julvez et al., 1998; Machdar et al., 2013; Oguntoke et al., 2009; Yongsi, 2010)
Coping mechanisms employed[†]		
Collecting rainwater/ from rivers, streams, shallow wells etc.	22 (69%)	(Abaje et al., 2009; Akinbo et al., 2010; Ako et al., 2009; Baker et al., 2013; Degbey et al., 2011; Dorice et al., 2008; Dos Santos et al., 2015; Endris et al., 2019; Essayagh et al., 2019; Julvez et al., 1998; Kone-Coulibaly et al., 2010; Machdar et al., 2013; Muti et al., 2014; Nkhuwa, 2003; Oguntoke et al., 2009; P.S. et al., 1999; Sakijege, 2019; Traoré et al., 2013; Ubosi, 2018; Usman et al., 2005; S. Winter, Dzombo, et al., 2019; Yilgwan et al., 2010; Yongsi, 2010)
Purchasing water from vendors	16 (50%)	(Abaje et al., 2009; Baker et al., 2013; Barzilay et al., 2011; Blanton et al., 2015; Dorice et al., 2008; Dos Santos et al., 2015; Dunne et al., 2001; Endris et al., 2019; Machdar et al., 2013; Oguntoke et al., 2009; P.S. et al., 1999; Stoler et al., 2012a; Traoré et al., 2013; Ubosi, 2018; Von Nguyen et al., 2014; S. Winter, Dzombo, et al., 2019)
Storing water in the households	11 (34%)	(Adane et al., 2017; Baker et al., 2013; Barzilay et al., 2011; Blanton et al., 2015; Dos Santos et al., 2015; Dunne et al., 2001; Machdar et al., 2013; Muti et al., 2014; Navab-Daneshmand et al., 2018; Stoler et al., 2012a; Von Nguyen et al., 2014)
Water treatment	8 (25%)	(Abaje et al., 2009; Barzilay et al., 2011; Blanton et al., 2015; Dorice et al., 2008; Dunne et al., 2001;

		Muti et al., 2014; Oguntoke et al., 2009; Yilgwan et al., 2010)
Drilling wells/boreholes	3 (9%)	(Degbey et al., 2011; Nkhuwa, 2003; Sakijege, 2019)
Purchasing water from neighbours	1 (3%)	(Sakijege, 2019)
Installing storage tanks in households	1 (3%)	(Sakijege, 2019)
Purchasing pumps for ground water	1 (3%)	(Sakijege, 2019)
Illegal water connections	1 (3%)	(Von Nguyen et al., 2014)
Health outcomes- Self reported†		
Diarrhoea	15 (47%)	(Adane et al., 2017; Akinbo et al., 2010; Barzilay et al., 2011; Dorice et al., 2008; Dos Santos et al., 2015; Dunne et al., 2001; Kone-Coulibaly et al., 2010; Muti et al., 2014; Navab-Daneshmand et al., 2018; Sakijege, 2019; Stoler et al., 2012a; Ubosi, 2018; S. Winter, Dzombo, et al., 2019; Yilgwan et al., 2010; Yongsi, 2010)
Cholera	4 (13%)	(Abaje et al., 2009; Blanton et al., 2015; Schaetti et al., 2013; Sinyange et al., 2018)
Dysentery	3 (9%)	(Abaje et al., 2009; Dorice et al., 2008; Sakijege, 2019)
Typhoid	3 (9%)	(Abaje et al., 2009; Dorice et al., 2008; Sakijege, 2019)
Clinically diagnosed†		
Cholera	8 (25%)	(Degbey et al., 2011; Essayagh et al., 2019; Kone-Coulibaly et al., 2010; Nkhuwa, 2003; Oguntoke et al., 2009; P.S. et al., 1999; Usman et al., 2005; Von Nguyen et al., 2014)
Typhoid	4 (13%)	(Ako et al., 2009; Degbey et al., 2011; Essayagh et al., 2019; Oguntoke et al., 2009)
Cryptosporidium	1 (3%)	(Machdar et al., 2013)
Amoebiasis	1 (4%)	(Degbey et al., 2011)
Diarrhoea (uncategorised)	3 (9%)	(Ako et al., 2009; Degbey et al., 2011; Traoré et al., 2013)
Moderate to severe diarrhoea	1 (3%)	(Baker et al., 2013)
Gastroenteritis	3 (9%)	(Ako et al., 2009; Degbey et al., 2011; Oguntoke et al., 2009)
Dysentery	3 (9%)	(Ako et al., 2009; Degbey et al., 2011; Oguntoke et al., 2009)
Rotavirus	1 (3%)	(Machdar et al., 2013)
Culture confirmed		
Typhoid	1 (3%)	(Muti et al., 2014)
Cholera	1 (3%)	(Endris et al., 2019)
Cryptosporidium	1 (3%)	(Akinbo et al., 2010)

†A study appeared in more than one category

Half of the studies (n=16, 50%) employed cross-sectional individual level study design, and only six percent (n=2) used cohort study designs, with the rest utilising case-control or cross-sectional ecological designs (Table 2). All these publications employed quantitative methods of data collection whereas only two publications (n=2, 6%) collected qualitative data to complement the quantitative data (Machdar et al., 2013; Sakijege, 2019). The studies' target population included general households or respondents (n=17, 53%), confirmed cases or patients in hospitals being treated for waterborne diseases/syndromes (n=6, 19%), children below 10 years (n=6, 19%), women or mothers of infants (n=3, 9%) and HIV infected persons (n=3, 9%). The study subjects ranged from less than 100 (n=2, 6%) to more than 500 (n=11, 34%) and nearly a third of the articles (32%) were targeting outbreaks from cholera (n=9) or typhoid (n=1), which are epidemic-prone waterborne diseases (Table 2).

To understand the association between water and waterborne diseases and syndromes, the studies mainly used bivariate and multivariate methods of analysis. The common bivariate analysis methods used included the chi-square tests, Fisher tests, Wald tests and the correlation coefficient methods while the multivariate analysis methods included regression models (linear, logistic, random effects) and ANOVA models. The multivariate analysis models controlled for confounders/ effect modifiers in the analysis using independent variables which included source of water, type of water storage container, presence of water treatment, household hygiene and sanitation conditions, household characteristics which included size, income, employment, and presence of children (Table 2). A study done by Machdar *et al* employed cost-effective analysis methods to assess the cost-effectiveness of interventions for reducing the disease burden from consumption of poor drinking water (Machdar et al., 2013).

Piped water was mainly supplied by the utility companies to residents through inhouse connections, shared taps at compound or public taps/ water kiosks (Adane et al., 2017; Dorice et al., 2008; Dos Santos et al., 2015; Ubosi, 2018; S. Winter, Dzombo, et al., 2019; Yongsi, 2010). However, the publications reported piped water insufficiency through proportion of the study population that had access to piped water (n=23, 72%), scheduled/ unpredictable water interruptions (n=8, 25%), per capita daily water availability (n=5, 16%) and time used/ distance to the water point (n=3, 9%). Four articles reported piped water inequality through the mode of access (n=3, 9%) (Dorice et al., 2008; Traoré et al., 2013; Yongsi, 2010), quantity (n=2, 6%) (Machdar et al., 2013; Traoré et al., 2013), cost (n=1, 3%) (Traoré et al., 2013) and the scheduled water interruptions (n=1, 3%) (Machdar et al., 2013).

The objective assessment of water safety was assessed by the studies via testing water samples (n=19, 59%). The water samples were collected from the dominant water points of the study population (n=9, 47%), water stored in the households (n=7, 37%), both dominant water points and stored water in the households (n=3, 16%) or hand rinse samples (n=1, 3%). Several studies assessed water contamination by testing for coliforms (n=17, 89%), effectiveness of measures of protecting water from contamination through testing for free residual chlorine (n=7, 37%), organoleptic characteristics of water by assessing turbidity and pH (32%, n=6) and presence of pathogens which included *klebsiella pneumoniae*, *staphylococcus aureus*, *pseudomonas aeruginosa*, among others (26%, n=5).

To complement their water needs, the study population employed coping mechanisms which included collecting rainwater/ water from rivers, streams or shallow wells (n=22, 69%), purchasing water either from vendors (n=16, 50%) or neighbours (n=1, 3%), storing water in the households (n=11, 34%), water treatment (n=8, 25%), drilling wells/ boreholes (n=3, 9%), installing storage tanks in households (n=1, 3%) and having illegal water connections (n=1, 3%) (Table 2). Four of the studies reported a relatively higher cost in the purchased water as compared to the cost of water supplied by the utility companies (Abaje et al., 2009; Sakijege, 2019; Stoler et al., 2012a; Traoré et al., 2013).

The publications focused on cholera (n=12, 38%), typhoid (n=8, 25%) and amoebiasis (n=2, 6%) as waterborne diseases, diarrhoea (n=20, 32%), dysentery (n=7, 22%) and gastroenteritis (n=3, 9%) as symptoms and cryptosporidium (n=2, 6%) and rotavirus (n=1, 3%) as etiological agents of diarrheal diseases. The health outcomes were either self-reported, clinically confirmed or objectively assessed through collecting and culturing stool samples.

The most common self-reported waterborne diseases/syndromes included diarrhoea (n=15, 47%), cholera (n=4, 13%), dysentery (n=3, 9%) and typhoid (n=3, 9%). The clinically confirmed health outcomes were cholera (n=8,25%), typhoid (n=4, 13%), cryptosporidium (n=1, 3%), amoebiasis (n=1, 3%), diarrhoea (n=3,9%), moderate to severe diarrhoea (n=1, 3%), gastroenteritis (n=3, 9%), dysentery (n=3, 9%) and rotavirus (n=1, 3%) while the culture confirmed health outcomes were typhoid (n=1, 3%), cholera (n=1, 3%) and cryptosporidium (n=1, 3%) (Table 2). One study reported mortality as well as morbidity of waterborne diseases and syndromes (Essayagh et al., 2019). A comprehensive table containing the study characteristics can be found in Annex 1.

3.4.3.2 Connectedness of the Study Designs Used

The connectedness in the study design methods used by the articles were assessed to understand the nexus between water sufficiency and health outcomes, as shown in Figure 4.1. The axes in the biplot represented the first two principal components of the input data which explained 27% of the total variability, showing weak correlation among the study designs.

The black triangle markers in Figure 4.1 represent the mean centres for the health outcomes and the characteristics of piped water supply that were studied by the articles. The correlation circle is portrayed by the uncoloured hollow black circle. The coloured confidence ellipses, which are plotted around the group mean points, represent the study design methods employed by the studies and the size of the ellipses are based on the variance of each group. The numbers represent each publication included in our study.

Figure 2: Included studies and study design types, plotted against the first two principal components derived from study design characteristics

From this analysis, cross-sectional individual-level, cross-sectional ecological level, and case control studies were observed to have a high variance and were the three commonly used study designs. Cross-sectional individual study designs were generally used in self-reported health outcomes while cross-sectional ecological and case control study designs were used in assessing clinically confirmed and culture confirmed health outcomes respectively. Water quantity and quality were mainly assessed using cross-sectional individual and ecological level study designs, whereas water access was mainly assessed using cross-sectional individual-level study designs. An unusual combination of self-reported typhoid and water quantity was observed as an outlier (Figure 2). Use of cohort study designs in assessing the association between waterborne diseases and syndromes and water sufficiency was under-utilised.

3.4.4. Discussion

This study presents the results of a scoping review on associations between water supply and waterborne diseases and syndromes in large cities across Africa. Majority of the studies had been published since 2005. The relationship between piped water sufficiency and waterborne diseases/syndromes has mainly been studied using cross-sectional individual level study designs employing bivariate statistical methods. The main measures of water sufficiency used are access levels to piped water and water quality assessments while the health indicators mainly used are self-reported or clinically confirmed health outcomes. Cohort study design methods, measure of availability of piped water using quantifiable measures that include either per capita daily water consumption or water interruptions, cryptosporidium, cyclosporiasis, amoebiasis, rotavirus water borne diseases and culture confirmed assessment of health outcomes have been under-utilised. Similarly, multivariate methods which are important in assessing the confounders or alternative transmission pathways have been seldomly used.

Piped water has been listed as the primary source of improved water in this region (World Bank and Infrastructure Consortium for Africa, 2010), however results from this review contest to this with no evidence of sufficient piped water supply in the urban areas. Daily per capita water consumption and mode of access have been reported to be inversely proportional to the level of health concern, in outbreak and non-outbreak conditions (WHO, 2020a). However, these two variables were under-studied and only assessed by two studies, neither of which investigated an outbreak (Abaje et al., 2009; Dos Santos et al., 2015).

The use of alternative or secondary water sources, that are often unimproved (as classified by the Joint Monitoring Programme (JMP) of the World Health Organisation (WHO) and United Nation's International Children's Emergency Fund (UNICEF)), have been listed as one of the prevalent transmission pathways for water-related pathogens, due to high exposure to faecal contamination (Bain et al., 2014; WHO, 1993). Adequate water treatment has the potential to reduce contamination of these water supplies by half (Barzilay et al., 2011). The studies included in this review reported use of alternative water sources as a key coping mechanism for poor or intermittent water supply while only a small proportion reported use of water treatment. Water contamination tests were a common assessment of water quality, contributing to the increased evidence of contamination in the predominant coping mechanisms employed by residents in urban areas.

Water storage, which was the second major coping mechanisms employed by the residents in urban areas, was observed as having the potential to increase the burden associated with waterborne diseases and syndromes. Low income earners, who account for 61% of the population in Africa, regularly practice poor water storage (African Development Bank, 2011; Amrose et al., 2015). On the other hand, residents with a high income mainly invest in large storage tanks to ensure they enjoy safe storage and adequate water consumption even during periods of irregular water supply (Ledant, 2013). The in-depth qualitative assessment of poor water storage practices and their association with waterborne diseases was under-studied. None of the studies focused on user reported organoleptic characteristics of stored water in their households.

Diarrhoea and cholera were the majorly self-reported and clinically confirmed health outcomes respectively while cryptosporidium, cyclosporiasis, amoebiasis, rotavirus water borne diseases were under-studied. These four waterborne diseases are among the major etiological agents associated with moderate to severe diarrhoea in children below five years (Levine et al., 2020; World Gastroenterology Organisation, 2012). Additionally, clinically and culture confirmed health outcomes are the two main approaches used in case definition of diseases of public health concern, with cases confirmed through objective assessment of samples at the laboratory (WHO and CDC, 2010). However, culturally confirmed health outcomes were seldomly employed in these studies, making it difficult to assess the public health burden associated with waterborne diseases.

Cross-sectional ecological and individual-level studies and case control studies were the main study designs used to understand the association between water sufficiency and health. Cohort study designs and multivariate statistical methods were under-utilised, limiting the detection of hotspots.

One of the limitations of this study was a lack of studies in Luanda, Kinshasa, Cairo, Johannesburg, Khartoum cities that had a population of more than 5 million people as at 2014 and are expected to be mega-cities by 2030 (UN-DESA, 2014). Furthermore, there were no studies on cyclopsoriasis which was one of the waterborne diseases under our study criteria. Another limitation of this study was potential bias introduced through the choice of databases to conduct the search. Furthermore, there was no omission of studies based on the quality appraisal conducted on the included publications. These limitations have also been reported in other scoping reviews (Pham et al., 2014). The use of a non-conventional analysis method in this review may have also been a limitation assessing the connectedness of the study designs, health outcomes, water sufficiency and assessment of water quality. Similarly, the analysis methods deviated from the published protocol found here (Mutono et al., 2020), and in annex 3 where proposal had been made to conduct cluster analysis to differentiate self-reported diarrheal diseases with etiological agents. This was not possible due to the diverging water sufficiency characteristics reported by the studies. Digital maps which overlayed the study locations and the water scarcity peer reviewed maps, as stated in the scoping review protocol were also not presented. This is because the main outcome of our study was depicting underutilised study designs, health outcomes and water sufficiency metrics.

3.4.5 Conclusion

Monitoring of health outcomes and the trends in availability and mode of access of piped water should be prioritised in urban areas in Africa in order to implement interventions towards reducing the burden associated with waterborne diseases and syndromes. This will contribute towards understanding the exposure pathways. Similarly, this is an area that can be used to assess the strategies of Africa being closer to achieving the United Nations Sustainable Development Goals regarding sustainable cities, adequate water, good health and wellbeing of its citizens and the Africa Union aspiration of having an African continent that is based on growth and sustainable development while coping with water insufficiency.

Chapter Four: Results for Objective One

4.0 Spatio-Temporal Patterns of Domestic Water Distribution, Consumption, and Sufficiency in Nairobi City

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4.1. Introduction

Many cities struggle to supply water to their residents both due to rapid population growth through urbanisation, and in some regions, because of water scarcity (UNESCO and UN-Water, 2020). Revenue recovery among low-income neighbourhoods can be challenging, as can service delivery in unplanned, informal neighbourhoods (Dagdeviren and Robertson, 2011). There is concern that progress in informal urban neighbourhoods lags substantially behind formal neighbourhoods, and that data aggregated to city scale may mask such localised variation in progress to widening access to safe drinking water (Cetrulo et al., 2020).

To ensure monitoring of the Sustainable Development Goals (SGDs), the Joint Monitoring Programme (JMP) routinely measures inequalities from cross-sectional household surveys and censuses at national level, whilst several studies have used such data to examine inequalities in water access at household level through to national scale (Adams, 2018; S. Chaudhuri and Roy, 2017). However, studies of changing inequalities over time remain scarce at the sub-national and particularly the city scale, given this reliance on cross-sectional data sources.

Inequalities in safe water access are frequently measured through source type (often classified according to the JMP's ladder), such as access to tap water (Malakar et al., 2018). Some studies have incorporated other dimensions of water service delivery, notably water quality (Yang et al., 2013), but there are relatively few studies that have examined intra-urban differences in volumes of water consumed (Adams, 2018). This is despite recognition via the incorporation of safely managed water services into SDG 6.1.1. Safely managed water services recognise the importance of providing water on premises, the availability of water when needed (and implicitly having sufficient volumes of water to meet basic needs), its safety and affordability. Those that have studied transition of safer water access typically rely on the type of source used, for example, improved versus unimproved for Nairobi (Iddi et al., 2021).

In low-income urban areas, relatively low water consumption rates per household make water provision there less commercially attractive than in middle or high-income areas (Boakye-Ansah et al., 2019). This is particularly so where low volume consumers benefit from reduced tariffs per cubic metre via progressive tariff structures(Castro and Morel, 2008). The risk to service providers is further exacerbated by greater illegal connection rates and non-revenue water in such areas. In many low and middle income countries (LMIC) cities, expansion of low-income neighbourhoods is unplanned, spontaneous and unregulated, with large proportions of Sub-Saharan Africa's urban population living in such informal settlements (Castro and Morel, 2008). This unplanned nature of low-income urban growth is a further challenge for water service delivery(Boakye-Ansah et al., 2019).

Given the paucity of studies at the city scale of changing inequalities in water access, the objectives of this study was therefore to examine inter-neighbourhood variation in sufficiency of domestic water consumed in relation to neighbourhood type and age, and how these data have changed over time. In examining neighbourhood age, we sought to understand the extent to which service delivery may be delayed or impacted in newly developed low-income urban neighbourhoods. In doing so, we drew on utility consumption records for the city of Nairobi, Kenya, disaggregated to fine spatial resolution, supplementing these with ancillary geospatial data to characterise Nairobi's neighbourhoods at fine spatial resolution.

4.2 Materials and Methods

4.2.1 Study Setting

Nairobi is the largest city in Kenya with an estimated 4.4 million people (Kenya National Bureau of Statistics, 2019). It is one of the 47 counties in Kenya and covers an area of 645 km^2 with a population density of 6,247 people per km^2. The estimated population growth of Nairobi is 4% annually (World Bank, 2020).

4.2.1.1 Water sources, Treatment, and Distribution Network

Constituted as a company in 2003, Nairobi City Water and Sewerage Company (NCWSC) is responsible for water production and distribution in Nairobi. NCWSC is the sole distributor of piped water in the city and is charged with the mandate of equitably providing clean water and sewerage services to the residents of the city.

Nairobi receives its water from three dams (Ruiru dam, Sasumua dam, Thika dam) and one water spring (Kikuyu Springs). The three dams receive water from rivers that originate from the Aberdare Ranges. The Kikuyu water springs recharge from an aquifer in the Limuru area in Kiambu County neighbouring Nairobi.

Kikuyu springs*:* This was the first and main source of safe drinking water for residents of Nairobi between 1901 and 1950. The springs recharge from an aquifer estimated to cover 161 km^2 with an annual recharge of 13.2 billion litres. The water from the springs is chlorinated at the source and discharged to the Kabete service reservoir before onward distribution to the Nairobi city residents. Half (51%) of the water in Kikuyu Springs is abstracted through boreholes (Water Resources Authority, 2018).

Ruiru dam*:* This is the oldest of the three dams. Its construction was finalised in 1950 becoming the second main source of water supplied in Nairobi County after Kikuyu Springs. The dam receives water from the Ruiru river and transmits the untreated water to Ruiru junction where it is mixed with the treated water from Sasumua dam and transmitted to the Kabete service reservoir.

Sasumua dam*:* This is the second oldest of the three dams. Located on the Sasumua stream, a tributary of the River Chania, the dam became functional in 1956. The dam transmits raw water to the Sasumua treatment plant. The treated water is transmitted to Kabete service reservoir via Ruiru junction where it is combined with raw water from Ruiru dam.

Thika dam*:* This is the newest of the three dams, becoming operational in 1994 (Olima and K'Akumu, 1999). With a reservoir capacity of 70 billion litres, Thika dam is the largest of the three dams that supply water to Nairobi. The dam receives water from three sources: Thika river which provides 50% of the water, Githika river (30%) and Kayuyu river (20%). The raw water from Thika dam is transferred to Chania River through a tunnel with additional flows from Kiama and Kimakia weirs. The water in Chania River is then abstracted through another tunnel that is also fed by water from

Mwagu weir and transmitted to Ngethu water treatment plant. After treatment, the water is transmitted to Gigiri service reservoir in Nairobi County.

Figure 3 shows the locations of the main sources of water for Nairobi, the treatment plants, and the distribution network of the piped water in the city.

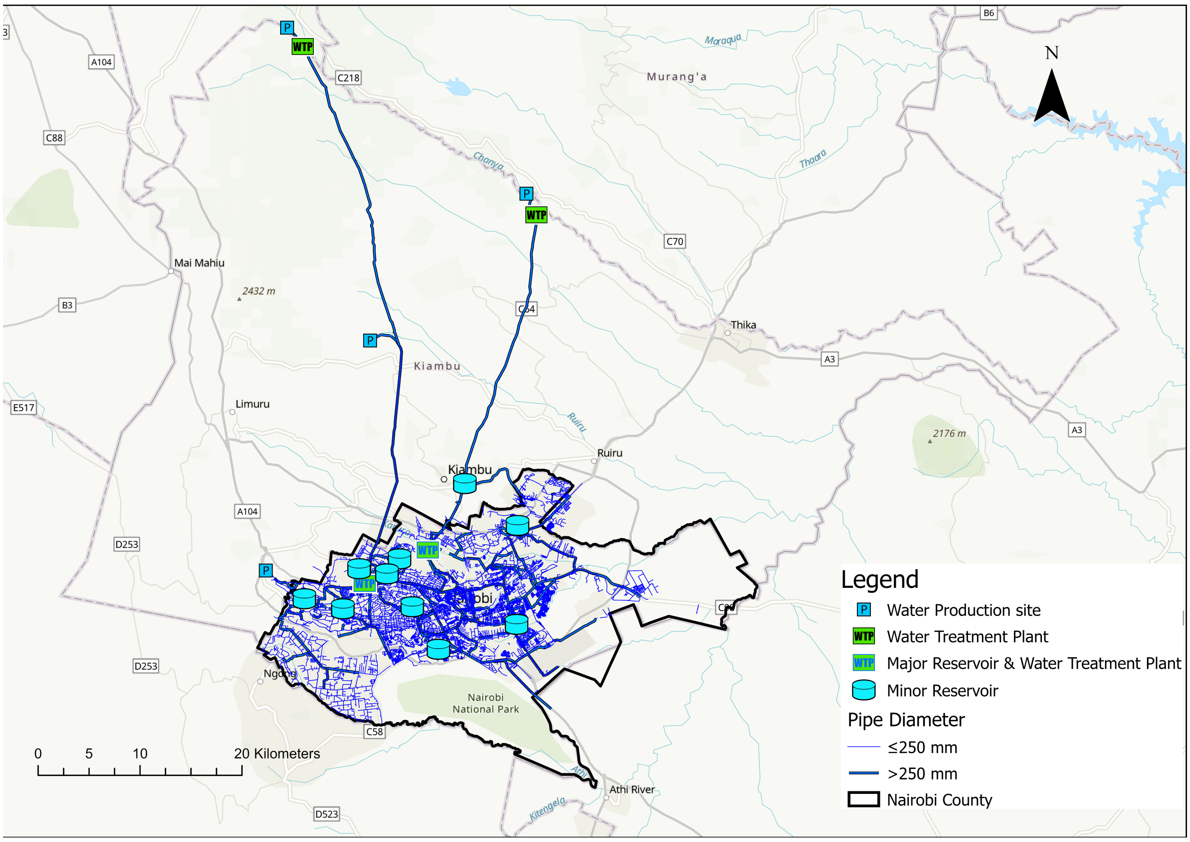


Figure 3: Piped water distribution system for Nairobi County showing water sources, treatment plants, water diameter pipelines and water service reservoirs. Source: Open Street Map (Haklay and Weber, 2008).

Water transmission from the dams and the springs to the service reservoirs is gravity-fed. Of the four water sources for Nairobi County, only Sasumua and Thika dams have the capacity to treat the raw water (Sasumua and Ngethu treatment plants respectively) before transmission to the two main service reservoirs (Gigiri and Kabete) for the city. The Gigiri and Kabete service reservoirs, with a daily gross yield of 401 and 77.6 million litres respectively, serve as water treatment sites before piped distribution to the consumers.

The treatment process at the service reservoirs and the water treatment plants near the dams starts with sedimentation either through the horizontal-flow or vertical-flow process. The water then goes through rapid gravity sand filtration, disinfection through chlorination and pH adjustment by the addition of soda ash (anhydrous sodium carbonate). The last step is coagulation using alum (hydrated double sulphate of aluminium and potassium). The treated water is then distributed from the service reservoir to the consumers.

The Gigiri service reservoir, which distributes 84% of the piped water consumed in Nairobi County, pumps 8% (32 million litres/day) of its water to Kabete service reservoir to meet shortfall in supply from Kabete sources. Kabete service reservoir mainly distributes water to the central and western parts of the city. The eastern side of the city mainly receives water from Gigiri service reservoir.

Eleven minor service reservoirs, six from Gigiri service reservoir (Kiambu, Karura, Kasarani, Outering, Wilson, Embakasi) and five from Kabete service reservoir (Kyuna, Dagoretti Forest, Uthiru, Hill Tank, Loresho) distribute water across the city. The water is pressurised through pump stations (Kabete, Gigiri, Kenyatta Avenue, Loresho) at different points of the distribution network (Figure 3).

A summary of the characteristics of the four main sources of water for Nairobi County is provided in Table 3.

Table 3: Characteristics of the main sources of piped water supplied in Nairobi County

Parameter	Thika Dam	Sasumua Dam	Ruiru Dam	Kikuyu Springs
Year of operation	1994	1956	1950	1901
Height (metres)	65	42	23	Not applicable
Source of water	River Thika, River Githika, River Kayuyu	Sasumua stream	River Ruiru	Kikuyu Springs Aquifer
Reservoir/recharge capacity (million litres)	70,000	19,000	3,000	13,000
Gross yield capacity (litres/day)	460,000,000	59,000,000	22,700,000	4,800,000
Daily transmission (litres/day)	430,000,000	56,200,000	21,700,000	1,440,000
Capacity utilised	93%	95%	96%	30%
Treatment plant	Ngethu water treatment works	Sasumua treatment works	None	Chlorination at the springs
Major service reservoir served†	Gigiri	Kabete	Kabete	Kabete

† Additional water treatment happens at the major service reservoir before distribution

Source: Nairobi City Water and Sewerage Company, Global Reservoir and Dam Database (Lehner et al., 2011)

4.2.1.2 Water Distribution by Residential Classification

The initial water distribution network for Nairobi was centred on the different residential areas that were using the Kabete service reservoir (van Zwanenberg, 1975). To cater for the increase in population, the first comprehensive water distribution plans were developed in 1985 by the Water and Sewerage department of the Nairobi City Commission. These plans used the residential area categories in the 1979 land use maps that were derived from the 1973 Nairobi Metropolitan Growth Strategy (Kingoriah, 1983).

The residential areas were divided into four categories (Residential areas 1-4) based on income, population density and type of housing. Residential areas 1 (R1) were the high-income areas characterised mainly by detached houses and modern houses often with medium to large gardens, low population density of less than 5,000 people per square kilometre and residents earning a monthly income of more than $29 per household. Residential areas 2 (R2) were the middle-income areas characterised by housing estate developments and flats, mixed with small commercial areas and a medium population density of 6,000-8,000 people per square kilometre. The residents had a monthly income of between $11 and $29 per household. Residential areas 3 (R3) were the middle/low-income areas characterised by flats and houses in older city areas, mixed with small commercial and light industrial areas and a medium to high population density of 9,000 to 11,000 people per square kilometre. Residential areas 4 (R4) comprised of areas with low-income housing and unauthorised shanty dwellings and a high population density of more than 11,000 people per square kilometre. The monthly income of residents in R3 and R4 was $6 to $11 and below $6 respectively. High- and middle-income areas predominantly accessed piped water through direct household connections while middle/low and low-income areas primarily accessed piped water through shared taps at yard/compound and water kiosks respectively.

Over the years, the type of piped water access has been maintained while the water distribution in the city has been updated by adding new customers to the network, with residential areas developed after 1985 being assigned to one of the four existing residential categories. In 2018, the land use maps were updated using the 2014 Nairobi Integrated Urban Development Master Plan that incorporated the 1973 Master Plan, the growth in population and the land use changes between 1979 and 2014 (Nairobi City County, 2014).

To enable easy control and monitoring of the amount of water distributed for billing purposes and the process of adding more customers to the system, the NCWSC groups water customers into small geographical units referred to as itineraries. Each itinerary has an average of 700 people. During periods of water shortages, NCWSC rations the water by having programs on number of hours and days itineraries are supplied with water per week. The rationing programs are revised every six to twelve months, with occasional delays.

4.2.1.3 Domestic tariff structure for water produced by NCWSC

The water tariff structure for Nairobi is prepared by the Nairobi City Water and Sewerage Company. This tariff remained unchanged for the periods of 2015 to 2018. For water supplied to residential areas through direct household connections, a flat rate of US $1.89 was charged for monthly water consumption of <7,000 litres. Monthly consumption between 7,000 to 60,000 litres was charged at US $0.49 per 1000 litres. Additional consumption above 60,000 litres was charged at US $0.59/1000 litres.

For water supplied to shared taps in yards/compounds and to water kiosks, the recommended retail price was $0.49 and $0.19 per 1000 litres respectively. However, the water kiosks were privately owned and NCWSC was only able to recommend but not enforce the water rates.

4.2.2 Data Sources

To understand the water distribution patterns for Nairobi County, data from NCWSC on the monthly water outflows for the main reservoirs that distribute water across

Nairobi, data on volumes of water consumed in every itinerary, water rationing programs and population of every itinerary for the period 2008 to 2018 was obtained. The geographical locations of the itineraries and the 1985 and 2018 water distribution networks for Nairobi were also collected from NCWSC.

The population counts, density, monthly water production (water from the reservoirs), water distribution network, water access for the residential categories, volumes of monthly water consumption of piped water in every itinerary, monthly unit cost of water, water rationing data, geographical location of the itineraries and land use maps for 1985 were obtained from NCWSC. The land use maps for 2018 were obtained from the Kenya Ministry of Lands and Physical Planning. The data on water production was only available for the period November 2016 (when metering of this water started) to May 2018 (when breakages in the metering system happened).

The water consumption data for Nairobi is collected on a monthly basis from the customer's meter readings and used to bill the consumers. This data was aggregated to itineraries to de-identify the customers. Of the 3000 itineraries, 15% (n=554), which consisted of non-residential (20%, n=462) and residential (20%, n=92) itineraries, were filtered out due to lack of a geographical location, leaving 85% (n=2538) of itineraries grouped into either residential (n=2380, 94%) or non-residential (n=158, 6%) areas.

Gridded population data for each year from 2008 to 2018 was obtained from WorldPop (WorldPop, 2019). To calculate this population, WorldPop derive data from official country census data, administrative boundary maps and ancillary geospatial data sets such as road networks, hospital facilities, satellite imagery and buildings or settlements maps. Aggregate population counts for census areas are re-distributed within each boundary onto constituent 100 by 100 metre grid cells. A random forest dasymetric mapping algorithm is used by WorldPop to predict the population in every 100 by 100 metre grid cells from covariates such as distance to urban areas, bare areas, settlement build-up areas, water bodies, roads and night-time lights among others. The covariates are weighted and used to project population to the grid cells which is then aggregated to administrative boundaries and the accuracy assessed using predictions from freely available population datasets which include the Global Rural Urban Mapping Project and the Gridded Population of the World (Reed et al., 2018; Stevens et al., 2015). Annual population estimates are derived from a built-settlement growth modelling framework alongside successive census population estimates (Nieves et al., 2020).

To understand the association of neighbourhood age with volumes of water consumed per person per month, spatial data was acquired from the Global Human Settlement (GHS) project. The project categorises settlement typologies using built-up land cover based on the classification of the degree of urbanisation, as either cities, towns and suburbs or rural areas according to geographical contiguity (Florczyk et al., 2019). We used the GHS-Built map layer, which identifies the period when 30x30metre grid cells were converted to built-up land cover, based on multi-temporal classification of Landsat imagery from 1975, 1990, 2000, and 2014.

To evaluate the Nairobi Water and Sewerage Company's residential classification's suitability for inequality assessment, data at a sublocation level was obtained from the 2012-2013 Kenya State of the Cities Baseline Survey (KSCBS) (World Bank Group, 2014). This multi-stage cluster survey measured household service access and socio-economic characteristics in 15 Kenyan cities in a representative sample of sub-locations. Data concerning 1137 household respondents within seven sublocations in Nairobi were included in the analysis.

4.2.3 Data Analysis

We calculated the population for every itinerary by carrying out spatial queries of the population raster files using Quantum Geographic Information System (QGIS) (QGIS Development Team, 2016). We compared population counts and density in 1985 when the water distribution network was developed with that of 2018. We analysed population trends within the four residential area types between 2008 and 2018. In addition, we calculated the per capita monthly water consumption for the different itineraries and examined spatial patterns of water sufficiency (defined as >1,500 litres per capita/month) across the study period.

Since small area statistics at sublocation level are unavailable for either the 2009 or 2019 Kenyan population census, we used the utility's residential classification to examine neighbourhood inequalities in monthly water consumption over time. To evaluate the classification as a proxy for the socio-economic status of different neighbourhoods, we first cross-tabulated utility residential classes against household characteristics in the KSCBS by linking itinerary boundaries to KSCBS sublocation boundaries. Household characteristics examined largely reflected UN-Habitat slum criteria (UN-HABITAT, 2018) and included security of tenure, type of toilet facility predominantly used by the household, durability of housing structure, and use of a storage tank with a capacity of more than 100 litres.

We calculated the total water distributed in Nairobi County and the per capita monthly water consumption in the four residential areas, analysed the proportion of residents in the different categories who had a monthly water consumption of more than 1,500 litres/capita/month and the non-revenue water for Nairobi County. In addition, we carried out a negative binomial linear mixed-effects model (with year as a random effect) to determine if there were differences in the monthly per capita water consumption among the four residential categories over the study period, the yearly population in the itinerary, age of the residential neighbourhood, classified into five ordinal values based on the predominant period when the itinerary's land cover became built-up (before 1975, 1975 to 1990, 1990 to 2000, 2000 to 2014, after 2014). Univariable model analysis was carried out and independent variables with a p value <0.2 were included into the multivariable model. The collinearity of the different independent variables in the model was carried out using the Variance Inflation Factor (VIF) method. Factors with a VIF of more than five were termed as highly correlated and their interaction was assessed with other independent factors, where those that had a VIF of less than three was retained (Zuur et al., 2010). We carried out model diagnostics by calculating scaled residuals and mapped residuals to check for patterns. We also tested for dispersion of residuals, spatial and temporal autocorrelation in residuals to see if there was over/under dispersion, any spatially or temporal correlated structure in the model that was unaccounted for respectively. The analysis was performed using the R statistical software (R Core Team, 2017a).

4.3. Results

4.3.1 Residential Areas and Population Size

The comparison of the characteristics of the 1985 and 2018 land use categories that guide water distribution in Nairobi showed a marked change in the population size and area size covered by each of the four categories. In 1985, the total residential area was 190 km^2, covering 29% of the total land in Nairobi County. By 2018, this area had increased by 115% to 408 km^2, with the total residential area covering 63% of Nairobi County (Table 4).

The middle/low-income residential category had the largest growth in area over the period (a five-fold increase) followed by the middle-income residential areas (a two-fold increase). This increase was mainly through conversion of areas previously designated as agricultural or open spaces to residential areas to accommodate the increase in population size (Figure 4). In terms of the proportion of the residential areas in Nairobi occupied by the various residential categories in 1985 and 2018, the largest increase was observed in middle/low-income areas (changing from 20% to 46%), and the largest decrease in the high-income areas (changing from 51% to 28%), Table 4.

Between 1985 and 2018, the Nairobi population increased by 278% from 1,162,000 to 4,197,880 people. During this period, the largest increases in population size by residential areas were observed in the low-income category (growing 4.4 times), and middle/low-income areas (2.9 times). Population growth in the high-income and middle-income areas was 0.7 times and 1.62 times respectively (Table 4). Almost a third (31%) of this population growth was due to shifts in classification areas. Pre-1986 non-residential areas transitioned to areas that were now converted to middle/low-income areas (16%, 659,154), middle-income areas (7%, 284,848), low-income areas (6%, 240,209) and high-income areas (1% 47,807). Furthermore, a small proportion of the middle/low (2%, 88,649), middle (1%, 40,189) and high (0.3%, 13,685) income areas transitioned to areas classified as low-income areas.

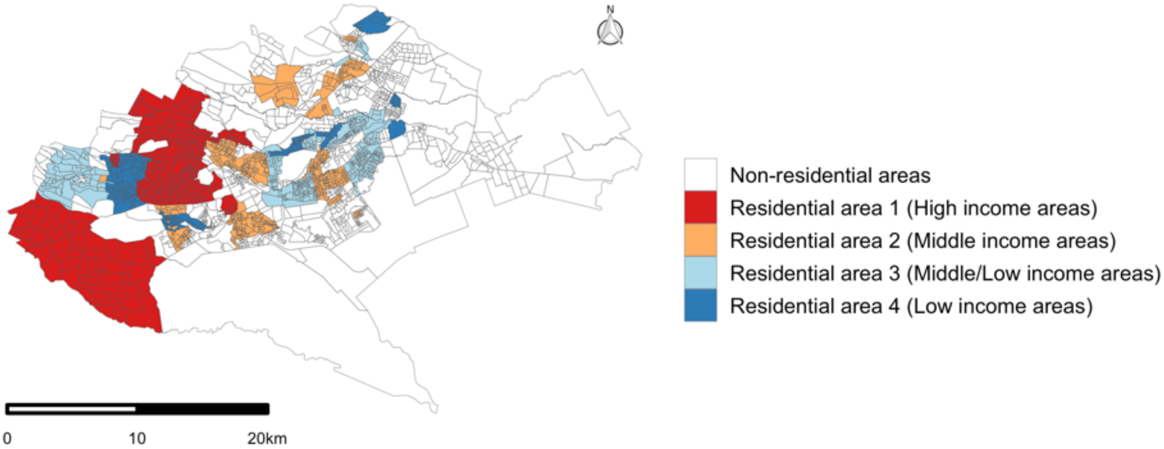
In 1985, monthly household income was classified as below \$6 for low-income areas and above \$29 for high income areas. By 2018, the classification had changed to above \$1800/month for high income areas while the low-income areas were classified as having a monthly revenue of less than \$360 per month. The monthly income classification for middle and middle/low-income areas had moved from \$11-\$29 and \$6-\$11 in 1985 to \$900-\$1800 and \$360-\$900 respectively (Table 4). Over the years, the primary water connection type in the residential categories has remained the same, with high- and middle-income areas accessing water through inhouse piped connection whereas the middle/low and low-income areas accessing water through shared taps at yard and water kiosks respectively.

Table 4: Characteristics of the different residential areas in Nairobi County in 1985 and 2018

Parameter	High income areas (R1) (%)	Middle income areas (R2) (%)	Middle/ low income areas (R3) (%)	Low income areas (R4) (%)
Total area (km²)				
1985	96.57 (51%)	36.02 (19%)	37.89 (20%)	19.44 (10%)
2018	113.05 (28%)	75.81 (19%)	189.23 (46%)	29.55 (7%)
Total population				
1985	139,000 (12%)	289,000 (25%)	460,000 (40%)	274,000 (23%)
2018	237,135 (6%)	757,393 (18%)	1,780,172 (42%)	1,423,180 (34%)
Minimum or maximum ranges of population density (people/km²)				
1985	<5,000	6,000-8,000	9,000-11,000	>11,000
2018	<4,500	4,500-13,500	13,500-18,000	<18,000
Range of household income (\$)				
1985	>29	11-29	6-11	<6
2018	>1800	900-1800	360-900	<360

Water connection type				
1985	Inhouse connection	Inhouse connection	Shared pipes at tap/yard	Water kiosks
2018	Inhouse connection	Inhouse connection	Shared pipes at tap/yard	Water kiosks

Source: Nairobi City Commission (Nairobi City Commission, 1985); WorldPop (WorldPop, 2019); Economic Survey 1985 (Central Bureau of Statistics, 1985); 2019 Kenya Population and Housing Census (Kenya National Bureau of Statistics, 2019); Africa Development Bank (African Development Bank, 2011)



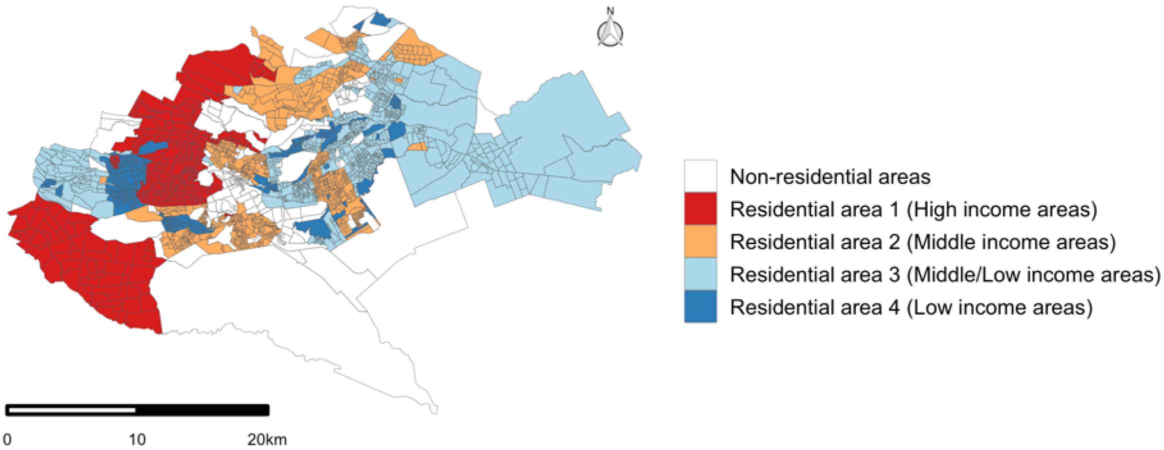


Figure 4: Residential and non-residential areas in Nairobi County in 1985 versus 2018. Source: Nairobi City Water and Sewerage Company, Survey of Kenya, Ministry of Lands and Physical Planning.

Comparison of the 2008 and 2018 population size in Nairobi shows a substantial change in the population of each of the four residential area categories. In 2008, the total population was 3 million, with middle/low and low-income areas comprising 43% and 28% respectively. This population had increased by 48% to 4.2 million by 2018 where three quarters of the population resided in both the middle/low (42%) and low-income areas (34%). The largest growth in population was observed in low-income areas and middle-income areas which had increased by 75% and 58% respectively. The population in middle/low-income areas had increased by 45%, while that in high income areas had decreased by 25% (Figure 4).

Compared to the previous year, a substantial population change was observed in 2013 in both high- and low-income areas, where there was a decrease of population by 42% (158,198) in high income areas and a 37% (371,020) increase in population in low-income areas (Figure 5).

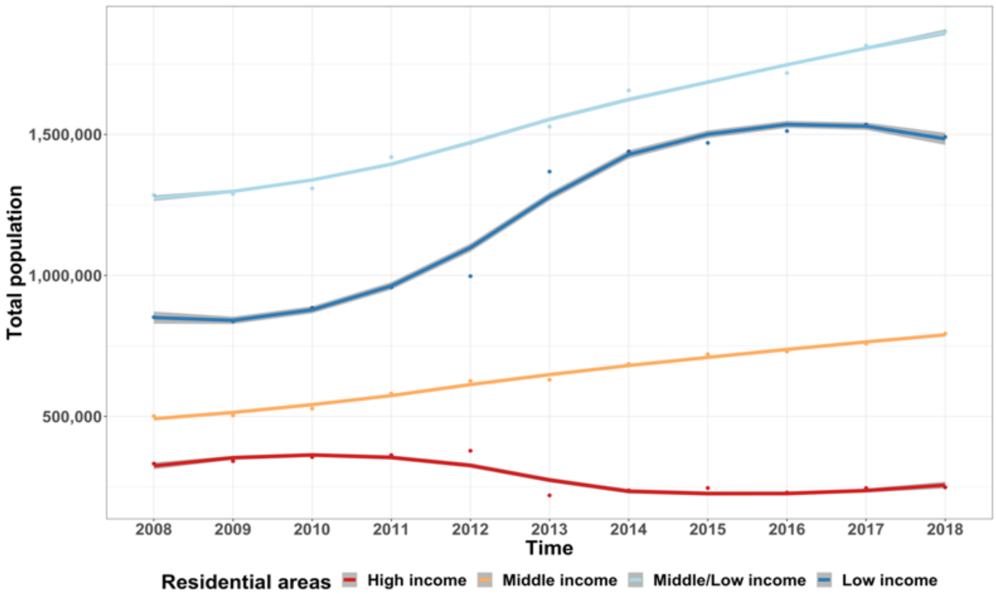


Figure 5: Population of the residential areas in Nairobi County from 2008 to 2018, classified by residential area type. Source: WorldPop and Nairobi City Water and Sewerage Company

4.3.2 Temporal Patterns of Production, Non-Revenue Water and Consumption

Data on water distribution in Nairobi County was available for the period 2008 – 2018. During this period, the total amount of water distributed increased gradually with residential areas consuming most of the water (82%) distributed by NCWSC, with non-residential areas only consuming 18% (Figure 6). The spikes observed are associated with rainy seasons (usually in March to May and November to December) during the study period. During periods of high rainfall, the utility company fully draws water from the rivers and only switch to discharging water from the dams when the rains recede. Maximum distribution of water from the dams continue until the levels are at 60% of the dam height when the rationing programmes are re-introduced.

In late 2012/2013 and 2014/2015, there were engineering modifications done at the treatment plants which included the increased height for the water filters and a total overhaul of the air valves along the transmission lines, resulting in increased water flows for treated water distributed in the city. These replacements are periodical with decreased efficiency of the transmission lines between replacement times.

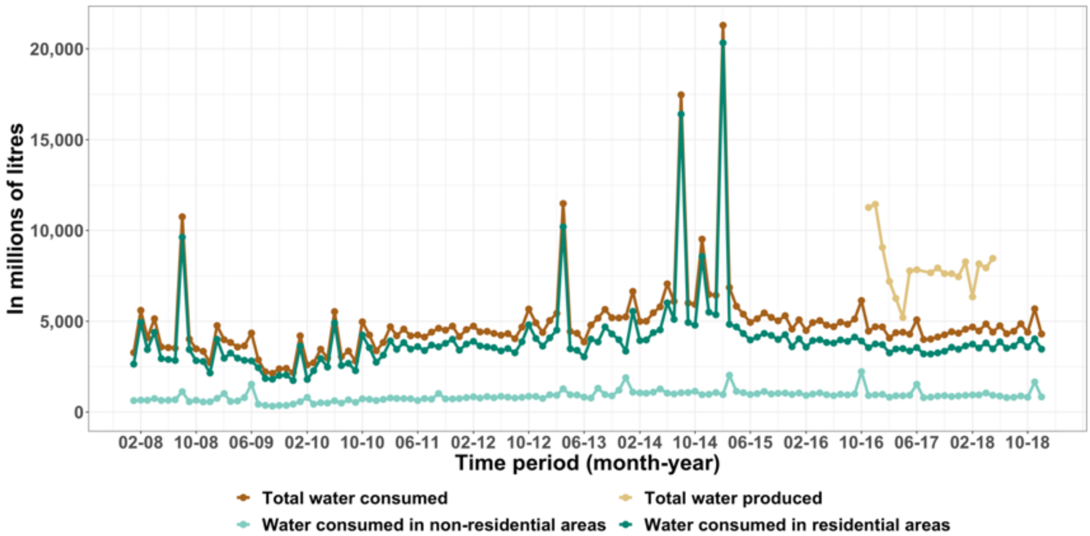


Figure 6: Residential versus non-residential monthly piped water consumption across Nairobi County from 2008 to 2018. The data for the total water consumed was only available for the period when the metering system at the major service reservoirs was functional

Data on non-revenue water lost through illegal connections, pipe bursts, water leakages, unmetered and irregular meters was only available for the period 2016-2018 (Figure 6). These data are calculated based on the amount of water released from the reservoirs and amount of water billed for by NCWSC. The non-revenue water loss averaged 3.5 billion litres of water per month, accounting for 29% of all water distributed across Nairobi County.

4.3.3 Residential Water Consumption by Neighbourhood Type

Comprehensive data on water rationing was available for the period 2016 to 2018. From these data, low-income areas recorded the highest number of hours receiving water while middle-income areas had the least number of hours. On average, the residents, starting from the high-income areas to low-income areas received water continuously for 59 hours (2.5 days), 50 hours (2.1 days), 65 hours (2.7 days) and 78 hours (3.3 days) respectively per week (Table 5). However, data on water consumption patterns shows the residents living in high- and middle-income areas had a monthly per capita water consumption of 13,087 litres and 6,240 litres respectively. Only a small proportion of residents in high-income (7%) and middle-income areas (12%) received less than the recommended 1,500 litres per capita per month.

The residents in low/middle income areas had a monthly per capita water consumption of 1,697 litres while low-income residents had a consumption of 827 litres. During the study period, an estimated 36% of the residents in low/middle income areas and 60% of residents in low-income areas had insufficient monthly consumption of piped water. These two residential area categories were at risk of water insufficiency with more than a third of their population constantly having per capita monthly water consumption of less than the recommended 1,500 litres (Figure 7). To ensure everyone had a continuous sufficient water consumption of at least 1,500 litres, an additional 1.5 billion litres/month would be required, an amount less than the estimated monthly non-revenue water.

Table 5: Average hours of weekly water supply per residential category in Nairobi County from October 2016 to December 2018 as per the water rationing programs

Period for water rationing programs	High-income areas (R1) (days)	Middle-income areas (R2) (days)	Middle/ low income areas (R3) (days)	Low-income areas (R4) (days)
July-December 2018	58 hours (2.4)	49 hours (2)	65 hours (2.7)	82 hours (3.4)
May-June 2018	54 hours (2.3)	44 hours (1.8)	58 hours (2.4)	68 hours (2.8)
January 2018- April 2018	54 hours (2.3)	45 hours (1.9)	58 hours (2.4)	68 hours (2.8)
October 2016- December 2017	69 hours (2.9)	61 hours (2.5)	78 hours (3.3)	93 hours (3.9)

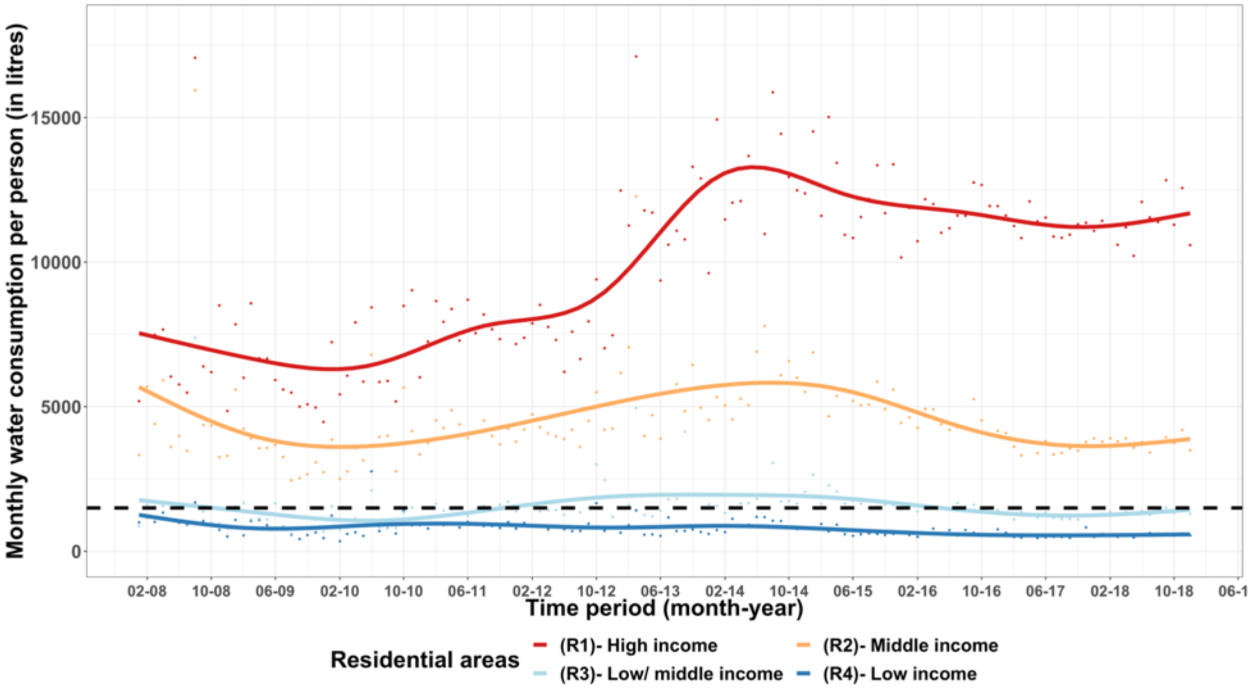


Figure 7: Water consumption per person in the four different residential categories. The dashed line shows minimum water requirements for domestic purposes (1,500 litres/capita/month as per Gleick (Gleick 1996)), while the dots are the monthly average water consumption in the itineraries per residential area type

4.3.3.1 Spatial-temporal Distribution of Water in Nairobi County

Visualisation of the spatial and temporal distribution of water in Nairobi County between 2008 and 2018 revealed several key patterns. First, for most years, water sufficiency was achieved for most residents in the periods between July and September (Figure 8). Secondly, there were spatial differences in water sufficiency with certain residential areas constantly experiencing water sufficiency while others were almost always insufficient. Thirdly, water insufficiency was higher during the later years of the study period with water insufficiency highest (83% of the year) in 2017, which was a severe drought period (Mwangi et al., 2014) and lowest in 2009 and 2010. From 2015-2018, the majority of residents had experienced water insufficiency for two thirds of the year (Figure 8).

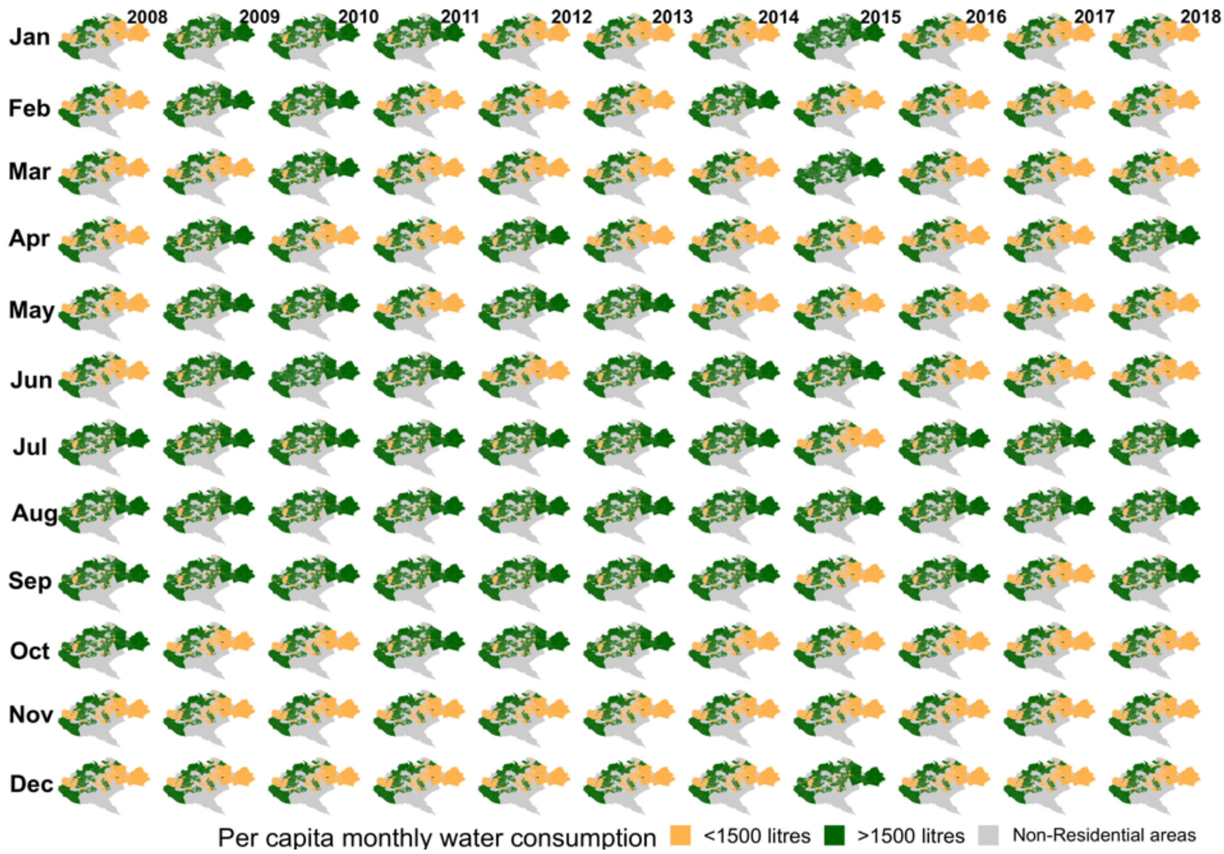


Figure 8: Spatial distribution of average per capita monthly water consumption for residential areas in Nairobi County from 2008 to 2018

We used the per capita monthly consumption to determine if there were significant differences in water sufficiency among the residential categories and the age of the residential neighbourhoods. We observed that, compared to residents in low-income areas, the likelihood of getting sufficient volumes of water per capita per month was six times (CI: 5.34-6.25) higher in high income areas, four times (CI: 3.52-4.10) in middle income areas and twice in middle/low-income areas (CI: 1.53-1.79) (Table 6). We found significant associations between the age of the residential neighbourhoods, interaction between age of residential neighbourhoods and the residential categories and population. Water consumption patterns were higher in newer neighbourhoods and areas with a lower population (Table 6). Additionally, the interaction between the age of the neighbourhood and residential category demonstrated higher likelihood in water sufficiency in the high- and middle-income areas, compared to low-income areas. The results of the goodness of fit tests on the model residuals included test dispersion of 0.873, temporal and spatial autocorrelation test of 0.267 and 0.028 respectively and zero unaccounted patterns both in the temporal and spatial graphs outputs. Similarly, the log likelihood ratio of the model was less than 0.001.

Table 6: Analysis of the monthly per capita water consumption by residential categories, age of built settlements and population for 2380 water distribution itineraries for Nairobi

Parameter	Number of itineraries per category (%)	Rate Ratio (*p* Value)	Confidence Interval
Residential category			
High-income areas	534 (22%)	5.78 (<0.001)	5.34-6.25
Middle-income areas	772 (32%)	3.80 (<0.001)	3.52-4.10
Middle/low-income areas	822 (35%)	1.65 (<0.001)	1.53-1.79
Low-income areas	252 (11%)	Reference category	
Built settlements			
Built up before 1975	579 (24%)	0.54 (0.425)	0.53-0.56
Built from 1975-1990	184 (8%)	0.62 (<0.001)	0.60-0.65
Built from 1990-2000	965 (41%)	0.87 (<0.001)	0.85-0.89
Built from 2000-2014	434 (18%)	0.96 (<0.001)	0.94-0.99
Built up after 2014	218 (9%)	Reference category	
Built up before 1975			
High-income areas	281 (48%)	2.85 (<0.001)	2.80-2.90
Middle-income areas	116 (20%)	2.34 (<0.001)	2.28-2.40
Middle/low-income areas	108 (19%)	0.72 (<0.001)	0.70-0.74
Low-income areas	74 (13%)	Reference category	
Built from 1975-1990			
High-income areas	20 (11%)	1.63 (<0.001)	1.60-1.66
Middle-income areas	102 (55%)	1.52 (<0.001)	1.47-1.59
Middle/low-income areas	42 (23%)	0.66 (<0.001)	0.63-0.69

Low-income areas	20 (11%)	Reference category	
Built from 1990-2000			
High-income areas	105 (11%)	2.21 (<0.001)	2.18-2.24
Middle-income areas	347 (36%)	1.73 (<0.001)	1.71-1.75
Middle/low-income areas	357 (37%)	0.67 (<0.001)	0.65-0.68
Low-income areas	147 (16%)	Reference category	
Built from 2000-2014			
High income areas	124 (28%)	2.20 (<0.001)	2.16-2.24
Middle income areas	103 (24%)	1.93 (<0.001)	1.90-1.96
Middle/low-income areas	185 (43%)	1.03 (0.409)	0.99-1.05
Low-income areas	22 (5%)	Reference category	
Population count		0.85 (<0.001)	0.71-0.93

Comparison of the utility's residential classes with KSCBS household data suggested residential class was a reasonable proxy for socio-economic status (Table 7). For example, proportion of households with secure tenure was 85% in the high-income residential class, but 48% in the low-income class. Similarly, the use of a storage tank with the capacity of more than 100 litres was 77% in the high- and middle-income areas but only 64% and 36% in the middle/low and low-income areas respectively. Flush toilets were predominantly used in the high (90%) and middle (84%) income areas while in only 52% and 34% of the middle/low and low-income areas respectively. Compared to the high- and middle-income areas, the use of shared pit latrines was relatively higher in low (49%) and middle/low (39%) income areas. Almost all the residents in high income areas (93%) had permanent household structures but only 45% in the low-income areas.

Table 7: Comparison of the demographics, water storage capacity, security of tenure, type of toilet facility and durability of housing structure among the utility's residential classes

Parameter	High-income areas (n=60)	Middle-income areas (n=170)	Middle/low-income areas (n=161)	Low-income areas (n=746)
Average number of people per room in the household	1	1	2	3
Use of a storage tank with a capacity of more than 100 litres	46 (77%)	131 (77%)	103 (64%)	271 (36%)
Security of tenure	51 (85%)	126 (74%)	94 (58%)	357 (48%)
Type of toilet facility				
- Flush toilet	54 (90%)	143 (84%)	83 (52%)	257 (34%)
- Pit latrine (individual)	6 (10%)	12 (7%)	13 (8%)	114 (15%)
- Pit latrine (shared)	0 (0%)	15 (9%)	63 (39%)	368 (49%)
- Flying toilet	0 (0%)	0 (0%)	1 (1%)	7 (1%)
Durability of housing structure				
- Permanent	56 (93%)	151 (89%)	111 (69%)	336 (45%)
- Semi-permanent	4 (7%)	19 (11%)	50 (31%)	410 (55%)

4.4 Discussion

Rapid urbanisation in developing countries in the absence of significant infrastructure growth threatens access to basic amenities including safe drinking water and adequate housing. In this study, we have reported an annual population growth rate of more than 4% between 2008 and 2018 and nearly three times increase in the total population of Nairobi between 1985 and 2008. Based on socio-economic status, the largest increase in population was observed in low-income residential areas and smallest increase in the high-income residential areas. In the last 50 years, only one new dam (commissioned in 1994) has been developed to improve supply of water to Nairobi. We reported large losses with non-revenue water accounting for nearly a third of all water distributed from the water service-reservoirs; an amount more than twice the number of litres required for all residents to access sufficient water. This study showed residents living in high-income areas were up to six times more likely to have sufficient water compared to residents in low-income areas, highlighting socio-economic inequalities in access to safe drinking water. Additionally, newer neighbourhoods, older neighbourhoods in high- and middle-income areas and less densely populated areas were more likely to enjoy water sufficiency.

Similar high urbanisation rates as observed in Nairobi have been reported in multiple cities in the African region (United Nations, 2018). The observation of most urban residents living in middle/low and low-income areas has been reported elsewhere, with the 2018 World Bank statistics reporting 54% of the urban population in sub-Saharan Africa to be residing in low-income areas (World Bank, 2018). The slow rate of growth in water infrastructure compared to population growth has also been reported in other cities in developing countries, which is mainly attributed to inadequate investment in water infrastructure (Mcdonald et al., 2014).

Whilst there have been several studies of spatio-temporal patterns of urban water distribution in developed countries (Donkor et al., 2014; House-Peters and Chang, 2011), such studies are rare in sub-Saharan Africa. This study is thus one of a small number of studies that have looked at spatio-temporal urban water distributions. The key findings of this study on socio economic inequalities in water access where residents of high and middle income areas access water through inhouse piped connection while middle/low and low income areas access the resource through shared tap at yard and water kiosks respectively have been reported in other studies conducted in Dar Es Salaam (Dill and Crow, 2014), Nairobi (Dill and Crow, 2014; Dos Santos et al., 2017) and Indian cities (Sidhwani, 2015).

To ensure equitable distribution of water, NCWSC implements a water rationing program. Despite a higher number of hours of water supply per week for middle/low and low-income areas compared to the high- and middle-income areas, low-income areas had higher levels of water insufficiency compared to high-income areas. These differences in water consumption may be explained by the mode of water access, water storage practices and the per unit cost of water. A previous study has reported residents with inhouse piped water connections to own larger water storage tanks that ensure continuous water supply (Cobacho et al., 2008). In Ghana, owners of water kiosks in low income areas retailed water at a cost higher than the price recommended by the utility company, resulting in the residents paying 9-13 times more on water, spending up to 20% of their daily wages (Monney et al., 2013). The cost of vended water in Nairobi has been reported to be $4.73 per thousand litres (Mitlin et al., 2019), more than double what is paid by households with direct water connection to their houses or shared taps in the yard/compound.

Non-revenue water has been estimated to account for 35% of the water distributed in developing countries (González-Gómez et al., 2011). The drivers for this high non-revenue water include high population density, using pumps to increase water pressure through the distribution network, intermittent water supply patterns and distribution to an increasing urban population among others (van den Berg, 2015). In this study, nearly a third of the water distributed was non-revenue water. This loss was more than twice (1.5 billion litres) the monthly amount of water required to ensure all the residential areas had a continuous, sufficient water consumption. Renovating the piped network and planning for water supply infrastructure are some of the main strategies recommended to minimise these losses (van den Berg, 2015). A pilot study conducted in a low income area in Nairobi to assess the impact of citizen engineering using mobile solutions to detect, report and repair water leaks outlined the potential of these technological solutions to reduce water losses by half (Heland et al., 2015). Similarly, Colombia was able to reduce non-revenue water loss by 7% through identifying and replacing the appropriate pipes in the water distribution network that contributed to major leaks in the system (Saldarriaga et al., 2010).

Water is a basic human right and every city should make provision of water that is reliable, safe, and affordable. The African Union Agenda 2063 and the 2030 United Nations Sustainable Development Goals aim to reduce the number of people without adequate water supply (African Union, 2015; United Nations, 2015b). By 2030, Nairobi City will be estimated to have over 7 million people (Mcdonald et al., 2014), indicating the need for improvement in the water distribution in residential areas, especially the group at risk. We found notable differences in water distribution between old and newer neighbourhoods and the interaction between neighbourhood age and residence type in Nairobi. Previous studies have reported inequalities in both housing and water distribution, which is driven by prioritisation of high and middle income areas during housing and infrastructure development and poor provision of piped water services in emerging poor neighbourhoods. (Blomkvist and Nilsson, 2017; Kyessi, 2005; Tusting et al., 2019; Watson, 2014).

Previous studies have reported governments as unwilling to provide water to these low-income areas, given the potential to legitimise residents' land tenure by providing services in such unplanned settlements (UN-Habitat, 2013). As having a piped water network might prove difficult in the short term, water kiosks, public taps, and number of days of water provision can be increased for the residents at risk to have relatively more water access. NCWSC has a pilot project where they are installing water dispensing systems in the low-income areas with the aim of improving the accessibility of water and making the commodity more affordable as demonstrated in Luanda, Angola (Maryati and Humaira, 2015).

There were several limitations to this study. The residential area classification and neighbourhood age was derived from the built environment, potentially omitting socio-economic conditions experienced by their residents while also excluding residential areas which were not in the water distribution grid. This problem has been highlighted in a study in both Kenya and Ghana showing the performance indicators used by water distribution companies may be insufficient to evaluate a population's access to safe water (Bellaubi and Visscher, 2014). However, since the data from the utility company were disaggregated spatially, instead of aggregated to the entire supply area, this addressed at least one related concern over the limitations of utility data. Another study limitation was the use of data on the 1985 population counts and population density from the NCWSC which was based on estimates calculated by the utility company using the 1979 national census and the average annual growth rate per residential category. In this study, we did not consider possible intra-itinerary variation, which may have led to the ecological fallacy problem, whereby results from data collected and analysed at a group level are assumed to apply to associations at the individual level (Sedgwick, 2015). Although we have used the 1500 litres per month amount to determine water sufficiency levels, the water supplied may have been used for both domestic and economic purposes leading to an overestimate of the proportion of population with sufficient water consumption. There are reports of economic activities in residential settings that rely on household water connections or water from the kiosks (Adank et al., 2012; Duran et al., 2004). There is however no widely accepted criterion that covers both domestic and economic uses of water in residential areas, a possible area of research to improve estimates of accessibility to safe drinking water for city residents. Data on shared connection types in itineraries and the extent to which residents accessed alternative safe sources of water in the absence of piped water was unavailable to account for in the analysis. We assumed the water connection type and water distribution programmes from the utility company matched well with the actual water connection types and distribution in the different residential area categories in the supply area respectively. In the absence of available small area statistics from the 2009 or 2019 Kenyan population censuses, we were only able to include three covariates in our spatio-temporal analysis of water sufficiency. However, comparison with socio-economic data from the KSCBS suggested that the utility's residential classification was a reasonable proxy for other socio-economic measures such as security of land tenure and durable housing.

4.5 Conclusion

From this study, we argue that equity in water distribution, from the mode of access, quantity, to infrastructure development should be prioritised to ensure improved safe water sufficiency for Nairobi. To actualise this, three things are critical: data, infrastructure investments and governance. Data on water supply and consumption is key in assessing the gaps in the water distribution process and to ensure sustainability in water sufficiency. Previously, accessibility of government data has been difficult in African countries where the data has been incomplete or manually stored. However, governments have been working towards ensuring their data is accessible, electronically stored, complete and consistent (United Nations Economic Commission for Africa, 2017) which enables research and future planning.

Improving water sufficiency will require the right investments from the national and international government. Growth in city population should be accompanied by investments in infrastructure to support provision of safe water to the population, including proper funding of water utility companies to enhance their performance (Mcdonald et al., 2014; van den Berg and Danilenko, 2017). The investments of water sufficiency should be categorised based on residential category and neighbourhood age, with focus on the groups at risk.

Finally, good governance that aims to minimise water losses and socio-inequalities is required. There should be deliberate prioritisation of water supply and infrastructure development in low-income areas, both in newer and older neighbourhoods, and densely populated areas, reduction in the non-revenue water and making safe water accessible and affordable to all. These are critical towards achieving the Sustainable Development Goal 6 of clean water and sanitation for all.

Chapter Five: Results for Objective Two

(Parts of this chapter have been published in the Frontiers in Health Services- Cost and Resource Allocation journal and can be accessed using this link: https://doi.org/10.3389/frhs.2022.788173).

5.1 Spatial Accessibility of Healthcare services in Nairobi City

Water plays a fundamental role in ensuring efficient urban health (Hunter et al., 2010). Specifically, a per capita monthly water consumption is required to ensure low levels of health concern (WHO, 2020a). However, the distribution of this resource has been experiencing inequality through access and quantity. Residents in lower middle income areas who are characterized by a household monthly income of less than $900, access water through shared taps at yard and water kiosks, and consume less than 1500 litres per person per month (Mutono et al., 2022). This group make up three quarters of the urban population in a rapidly urbanizing city, yet are at an increased risk of waterborne diseases (Mutono et al., 2022). Some of these water borne diseases, such as cholera and typhoid, are epidemic prone, and their outbreaks have increased in both frequency and magnitude over the last few years (Marchello et al., 2019; Rebaudet et al., 2013). To monitor cases from notifiable diseases, countries in the sub Saharan African (SSA) region have implemented a facility based surveillance system, the District Health Information System (DHIS), to track notifiable diseases, with cholera and typhoid being among them (WHO and CDC, 2010). As this hospital-based surveillance system requires patients to visit health facilities, before embarking on the risk of water insufficiency and health, we first needed to understand whether the data from the health facilities was a true representation of the population. To do this, we assessed the geographical accessibility of health facilities and the healthcare professionals available to the public.

An estimated 3.6 million deaths in low- and middle-income countries (LMICs) are associated with non-utilization of healthcare (Kruk et al., 2018). Timely healthcare access encompassing physical access to quality care, acceptability and financial access remains low in many developing economies despite its potential to substantially reduce mortality (Ouma et al., 2018; D. H. Peters et al., 2008).

Health is one of the measures of quality of life, and access to health facilities and to a skilled workforce in facilities has been prioritised by the United Nations through the Sustainable Development Goals. Goal 3 addresses better access to healthcare and the healthcare workforce with Target 3.8 seeking to achieve universal health coverage (UHC) for all by 2030, while Target 3.c aims to recruit, train, and retain the healthcare workforce in developing countries (United Nations, 2015a). Population access to these resources has been evaluated using geographical accessibility (Kapologwe et al., 2020; Ouma et al., 2018).

Geographical accessibility through distance or travel time has been reported as a significant barrier to effective treatment (Al-Taiar et al., 2008; Kuupiel et al., 2020). Optimal placement of health facilities that minimises travel distance to health facilities while maximising population coverage has been advocated (Airey, 1992; Toh et al., 2021). Research focusing on LMICs has used cost surfaces (for example, the World Health Organisation's (WHO) Access Mod software) and the two-step floating catchment area (2SFCA) method to measure geographical access (Kuupiel et al., 2020; McGrail, 2012; Ouma et al., 2018). However, cost surfaces are less well suited for quantifying patient travel in cities experiencing congestion as they expand and the associated challenges of timely access to urban secondary healthcare. On the other hand, the 2SFCA method calculates geographical accessibility of healthcare services through use of the gravity model to analyse the ratio of healthcare supply and population demand, while often incorporating patient mode of transport and road networks, and accounting for the population that has more than one health facility in its proximity (Luo and Qi, 2009; McGrail, 2012). However, there is limited research on the use of this method to assess the effect of traffic on the proportion of population with access to a health facility and the healthcare workforce, particularly in cities in LMICs which are characterised by rapid urbanisation and under-developed road infrastructure (Jain et al., 2012). Similarly, the healthcare workforce in Sub Saharan Africa is considerably under-resourced, with Kenya facing an unequal distribution of these personnel in the existing health facilities (Kirigia et al., 2008; Mezue et al., 2020).

Studies of peak and off-peak travel time to health facilities in Africa have primarily used methods that employ road networks (Fraser et al., 2020; Ouma et al., 2018). However, these studies focus on geographic access to emergency care without incorporating the ratio of population to healthcare workforce. Additionally, these studies consider traffic conditions for broad categories of road types, without including disaggregated traffic data. We investigated geographical access to healthcare facilities and professionals in an African city using the 2SFCA method while incorporating traffic data to address two research questions: i) How are healthcare facility catchment areas affected by traffic congestion? ii) How does traffic congestion influence the distribution of healthcare professionals to population across healthcare facilities?

5.1.1 Methods

5.1.1.1 Study Area

This study was conducted in Nairobi County, the most populous city in Kenya. The 2019 census data estimated Nairobi's population at 4.4 million with a population density of 6,247 per km^2 (Kenya National Bureau of Statistics, 2019).

In Kenya, health facilities are divided into four tiers based on the level of care offered. Tier I comprises community health services, providing mainly community health volunteer visits and health promotion messages. Tier II comprises the lowest level of health facilities that offer primary healthcare services (dispensaries, clinics, health centres and maternity centres). Tier III comprises sub-County hospitals, medium-sized and large private hospitals, County hospitals and large private teaching hospitals, which offer secondary healthcare services while, Tier IV are national referral hospitals that offer tertiary healthcare services (Figure 9) (Kenya Ministry of Health, 2014). Tiers I and II focus on health promotion and prevention, while Tiers III and IV prioritise curative services (Kenya Ministry of Health, 2014).

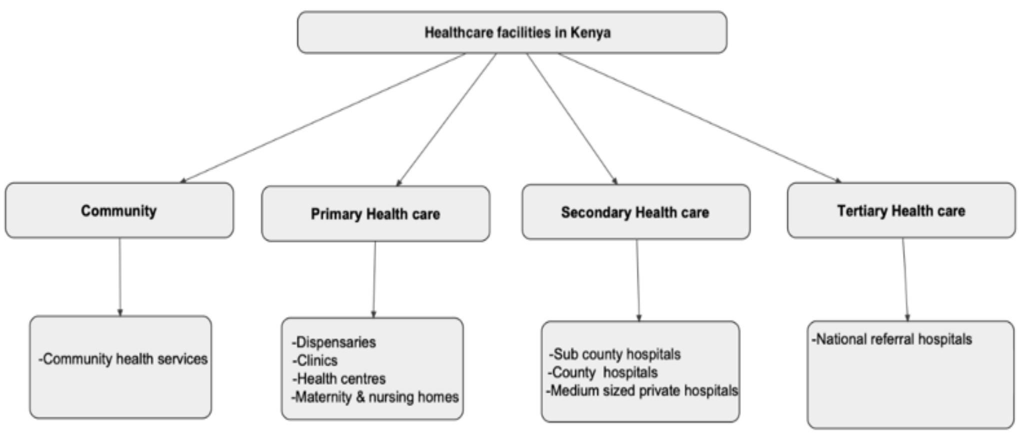


Figure 9: The four categories of healthcare in Kenya. Source: Kenya Health Policy 2014-2030 (Kenya Ministry of Health, 2014)

Since 2013, delivery of health services has been a devolved function of the county government, with the national government retaining the mandate of policy formulation and regulation (Masaba et al., 2020). In Nairobi County, service delivery via public health facilities is under the auspices of the Nairobi Metropolitan Services (NMS) (Nairobi City County, 2020). In 2020, Nairobi County had 1,042 health facilities registered under the Ministry of Health (Kenya Ministry of Health, 2020), yielding a ratio of 23.7 health facilities per 100,000 people. The majority (91%) of these facilities offered primary healthcare services while ~9% and ~1% offered secondary and tertiary healthcare services respectively. In addition, 74% of these health facilities were privately owned.

Kenya is one of two African countries for which the Environmental Systems Research Institute (ESRI) have online historical traffic data available to support drive-time calculations (Esri, 2020a). Approximately 88% of motorised public transport trips by urban residents in Kenya are in a *matatu* (a type of minibus) (Salon and Gulyani, 2019).

5.1.1.2 Facility Geocodes

In September 2020, we downloaded a list of health facilities registered in Nairobi from the Ministry of Health-Kenya Master Health Facility List (Kenya Ministry of Health, 2020). Public health facility coordinates were extracted from a previous study while private health facilities were geocoded using the street level precision of Google Earth Pro's geocoding service (version 7.3) which has low positional error (Maina et al., 2019; Ribeiro et al., 2014). Figure 10 gives a visualisation of the health facilities in Nairobi.

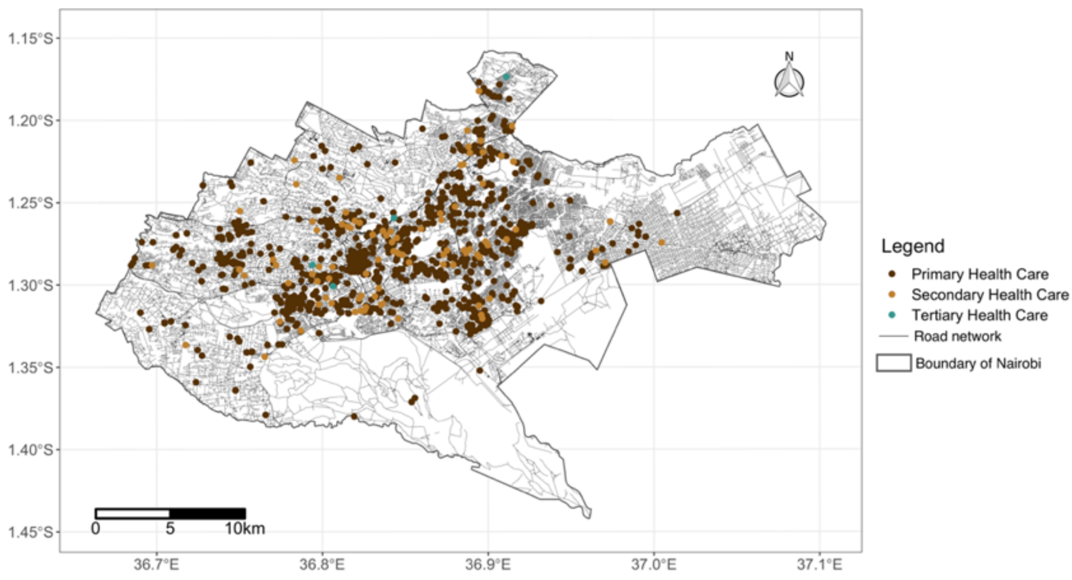


Figure 10: Road network coverage and locations of health facilities in Nairobi County, Kenya. Source: OpenStreetMap, Ministry of Health

5.1.1.3 Population Data

We used 2019 population data from WorldPop (WorldPop, 2020) which are calculated using official country census data, administrative boundary maps and ancillary geospatial data sets of road networks, hospital facilities, satellite imagery and building or settlement maps. The WorldPop group projected aggregate population counts from the 2009 census for sub-locations (areas with a mean population of 5,400) are projected to 2019 and re-distributed these within each boundary onto constituent 100 by 100 metres resolution grid cells. Using a random forest dasymetric mapping algorithm, which is an ensemble non-parametric modelling approach, WorldPop predicted the population in every grid cell from census data and a weighting scheme from covariates such as distance to urban areas, unvegetated areas, settlement built-up areas, water bodies, roads and night-time lights, among others (Stevens et al., 2015).

5.1.1.4 Health Facility Catchment Area

To estimate the catchment areas for healthcare facilities, we used ESRI routing services which collect historical traffic data from probes, which are global positioning system (GPS) enabled devices embedded in vehicles or carried by passengers (e.g. cell phones), and are able to relay their location in real time at frequent refresh rates (Z. Zhang et al., 2017). This system calculates distance- and time-based catchment areas for different transport modes, considering road networks and traffic regulations (Esri, 2020b). To analyse the impact of traffic congestion on motorised access to healthcare services relative to the catchment areas, we selected three cut-off times—15, 30 and 45 minutes—and compared travel times during randomly selected peak- and off-peak traffic hours. Peak hours included Monday 8am and Wednesday 6pm, while off-peak hours included Sunday 8am and Saturday 6pm.

We then computed the ratio of health facilities to the population using a two-step floating catchment area method adapted from Ahmed et al (Ahmed et al., 2019). In this method, the catchment areas of each health facility within a given threshold are calculated and the population within the catchment area is then tabulated. For population falling within the catchment area of more than one health facility per category, the ratios are summed up to assess the accessibility index for each population.

5.1.1.4.1 Ratio (R) of Health Facilities (F) to Population (P)

The population (P) that was within the travel time (tt_0) of each health facility (F) was calculated and the ratio of health facilities to the population R_f was computed using:

$$R_f = \frac{F}{\sum_{f \in tt_{f \le tt_0}} P_f}$$

We then calculated the population accessibility index by computing the ratio of health facilities to population in 100 by 100 metre grid cells. For populations with access to >1 healthcare facility within the travel threshold of each point representing the population, the ratio of healthcare facility to population for each level of facility was summed up. Population that was not within the catchment area of at least one health facility per category was defined as underserved. We used the Z-test to compare facility-level populations accessing health facilities during peak and off-peak hours.

5.1.1.4.2 Ratio of Healthcare Professionals to Population

We used average staffing levels for healthcare professionals across healthcare categories as reported in the Kenya Service Provision Assessment (KSPA) Survey of 2010 (Table 8) (National Coordinating Agency for Population and Development et al., 2011). The KSPA survey included 703 facilities which were randomly selected from the Master Health Facility List. Data on staffing were collected and averaged according to the level of care.

Table 8: The average number of healthcare professionals per facility in Kenya in 2011, by healthcare category

Health facility category	Primary	Secondary	Tertiary
Nurses/midwives	8	13	288
Clinical officers	3	4	30
Doctors	-	2	10
Total	**11**	**19**	**328**

Source: (National Coordinating Agency for Population and Development et al., 2011)

The population (P) that was within the travel time (tt_0) of healthcare professionals (HP) in each facility (*f*) was calculated and the ratio of healthcare professionals to the population R_{hp} was computed using:

$$R_{hp} = \frac{HP}{\sum_{f \in tt_{f \le tt_0}} P_{hp}}$$

We then calculated the population accessibility index by computing the ratio of healthcare professionals to population in 100 by 100 metre grid cells. For populations with access to >1 health facility within the travel threshold of each point representing the population, the ratio of healthcare professionals to population for each facility was summed. Populations outside facility catchment areas were considered inaccessible to healthcare professionals. We used the WHO recommendations of 4.45 healthcare professionals (doctors, clinical officers, nurses, midwives) per 1000 people to classify access as sub-optimal (<4.45:1000) or optimal (>4.45:1000) (World Health Organization, 2006). To cater for edge effects, we applied a 2.5-kilometre buffer from administrative boundaries, recalculated the healthcare professional to population ratio and recalculated the accessibility index before classifying access as either optimal or sub-optimal. The analysis and visualisation was conducted using R statistical software version 4.0.4 (R Core Team, 2017a).

5.1.2 Results

To quantify geographic access to healthcare, we first present data concerning the proportion of population within 15-, 30- and 45-minutes' drive of the nearest primary, secondary and tertiary healthcare facility, examining how these proportions vary during peak versus off-peak travel times. We then present population to healthcare professional ratios, drawing on the related two-step floating catchment analysis.

5.1.2.1 Catchment Areas for Health Facilities

The proportion of the population within the catchment areas of each level of healthcare that could access the healthcare facilities within ≤15, 30 and 45 minutes during off-peak hours was significantly reduced during peak traffic times. This was observed for all three levels of healthcare, except for secondary health facilities which were accessible to the whole population during peak and off-peak hours, at 45 minutes threshold (Table 9). During peak hours, 45%, 20% and 17% of the population could access primary, secondary, and tertiary health facilities respectively, within 15 minutes. During off-peak hours, access to primary, secondary, and tertiary health facilities increased by 3%, 23% and 13% ($p<0.001$) respectively. At 30 minutes, >50% of the population was able to access the three levels of health facilities, with the greatest proportion having access to primary healthcare during peak (68%) and off-peak (75%) hours. Tertiary healthcare had the lowest population access (55%) at 30 minutes during peak hours.

Table 9: Distribution of Nairobi's 4.4 million residents with 15, 30 and 45-minutes' drive-time access to health facilities during peak and off-peak traffic hours

Healthcare level	Time (min)	Population in millions (%)		*p*-value
		Peak hours	Off-peak hours	
Primary	<15 min	1.8 (45%)	2.0 (48%)	<0.001
	<30 min	2.8 (68%)	3.1 (75%)	<0.001
	<45 min	3.9 (95%)	4.0 (97%)	<0.001
Secondary	<15 min	0.8 (20%)	1.8 (43%)	<0.001
	<30 min	2.5 (62%)	2.9 (71%)	<0.001
	<45 min	4.1 (100%)	4.1 (100%)	1
Tertiary	<15 min	0.7 (17%)	1.3 (30%)	<0.001
	<30 min	2.3 (55%)	2.9 (71%)	<0.001
	<45 min	3.6 (86%)	3.7 (91%)	<0.001

5.1.2.2 Geographical Access to Primary Healthcare

The spatial coverage of facilities offering primary health care was predominantly in the central region of Nairobi County, during both peak and off-peak hours, with the peripheries underserved both during the peak and off-peak traffic times. In 15 minutes, only 2% and 8% of the population able to access health facilities had an accessibility index of ≥0.01 during peak and off-peak traffic times respectively. This meant that at least one health facility per 100 people was within the catchment area. The rest had an accessibility index of <0.01, with one health facility having more than 100 people within the given threshold. In 30 minutes, the proportion of the population with an accessibility index of at least one heath facility per 100 population increased to 16% and 18% during peak and off-peak traffic times respectively. In 45 minutes, two thirds of the population, 67% during peak time and 69% during off-peak hours had an accessibility index of one health facility offering primary health care to more than 100 people (<0.01) within the given threshold. The rest had at least one health facility per 100 people. On the other hand, less than 1% of the population, predominantly in the southwestern region, had a relatively higher accessibility index of at least two health facilities per 100 people within the three cut-off times, during peak and off-peak traffic periods (Figure 11).

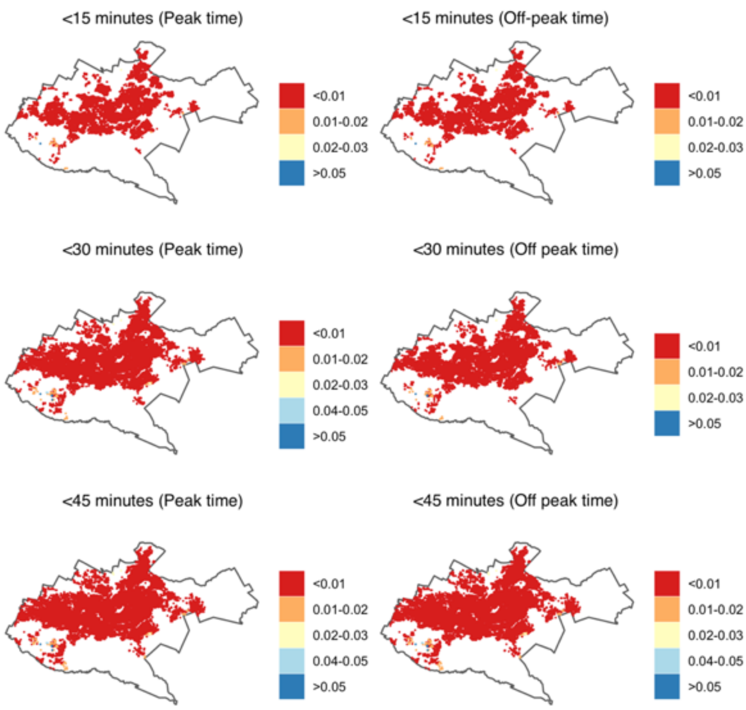


Figure 11: Accessibility index (population: facility ratios) for primary health care in Nairobi within 15-, 30- and 45-minutes' drive during peak and off-peak traffic times. The white areas have no accessibility to health facilities

5.1.2.3 Geographical Access to Secondary Healthcare

In secondary health care facilities, the coverage was mainly in the central region, with the peripheries having a relatively better coverage when compared to primary health care facilities. The accessibility index was lower than primary health care where one hospital was primarily within access to more than 10,000 people. However, in less than 30 minutes, this ratio increased to at least five facilities within access to 10,000 people. In 45 minutes, 75% and 78% of the population had an accessibility index of <0.0001 where one hospital was primarily within access to more than 10,000 people during peak and off-peak traffic times respectively. Less than 1% of the population had a relatively better accessibility ratio of at least two facilities accessible to more than 10,000 individuals. The peripheries were underserved in accessing the health facilities in less than 30 minutes during peak and off-peak traffic scenarios as they had no access to a facility (Figure 12).

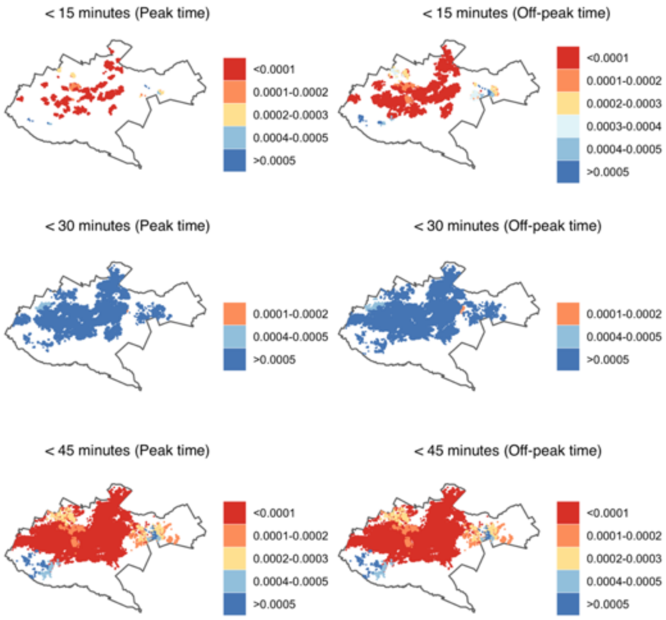


Figure 12: Accessibility index (population: facility ratios) for secondary healthcare in Nairobi within 15-, 30- and 45-minutes' drive during peak and off-peak traffic times. The white areas have no accessibility to health facilities

5.1.2.4 Geographical Access to Tertiary Healthcare

Similar to facilities offering primary and secondary health care, tertiary health facilities were mostly accessible to the population in the central region. The accessibility score of the number of health facilities to population ranged from 1 to 3 health facilities accessible to 100,000 people. In 45 minutes, 2% and 3% of the population had an accessibility score of more than 100,000 people to one facility whereas 80% and 86% of the population had a relatively better accessibility score of at least two facilities per 100,000 people during peak and off-peak traffic times respectively. The Eastern region and the peripheries were predominantly underserved with no secondary health facility within half an hour drive time during peak and off-peak traffic scenarios (Figure 13).

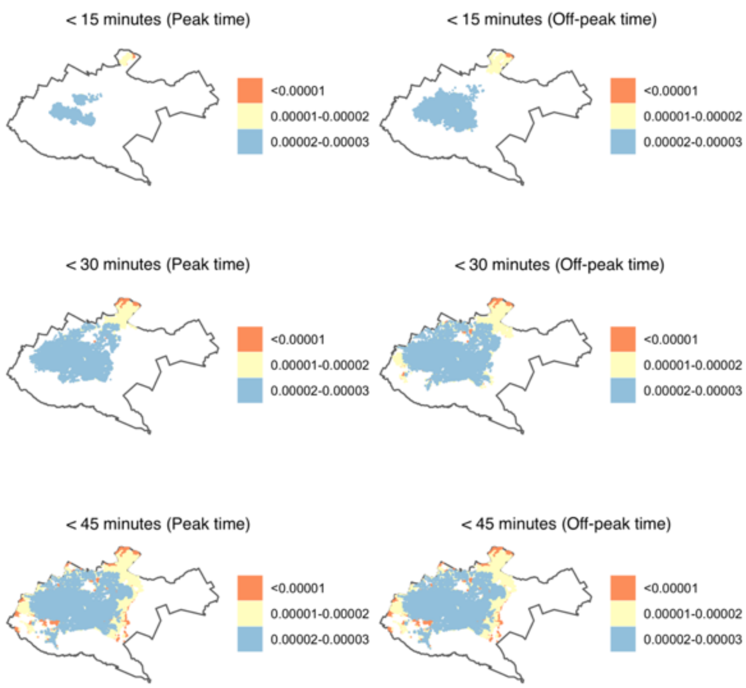


Figure 13: Accessibility index (population: facility ratios) for tertiary health care in Nairobi within 15-, 30- and 45-minutes' drive during peak and off-peak traffic times. The white areas have no accessibility to health facilities

5.1.2.5 Ratio of the Healthcare Professionals to the Population

All the population that was able to access health facilities offering tertiary care within 15 and 30 minutes had an optimal accessibility ratio of healthcare professionals which was above the recommended ratio of 4.45 per 1000 people during peak and off-peak traffic scenarios. On the other hand, secondary health care facilities had the highest proportion of population that had a sub-optimal ratio of below 4.45 healthcare professionals per 1000 people. In the proportion that was able to access secondary health care facilities in less than thirty minutes, more than 60% had a sub-optimal ratio of healthcare professionals during peak and off-peak traffic times. On the other hand, excluding population within 2.5 kilometre of the study area boundary significantly reduced the population with a sub-optimal ratio of healthcare professionals in all the facilities (primary, secondary, and tertiary) (Table 10).

Table 10: Population with a sub-optimal ratio of less than 4.45 healthcare professionals per 1000 within 15, 30 and 45 minutes of primary, secondary, and tertiary healthcare in Nairobi, during peak and off-peak traffic times

Healthcare level	**Time**	**Population in millions (%)**					
		< 4.45 healthcare workers per 1000 population (no buffer)			< 4.45 healthcare workers per 1000 population (2.5 km buffer included)		
		Peak	Off-peak	*p*-value	Peak	Off-peak	*p*-value
Primary	<15 min	0.2 (11%)	0.5 (25%)	<0.001	0.1 (11%)	0.3 (17%)	<0.001
	<30 min	1.0 (35%)	1.7 (55%)	<0.001	1.3 (33%)	1.5 (38%)	<0.001
	<45 min	2.5 (64%)	3.1 (78%)	<0.001	2.1 (53%)	2.6 (61%)	<0.001
Secondary	<15 min	0.8 (19%)	1.8 (44%)	<0.001	0.7 (17%)	1.6 (39%)	<0.001
	<30 min	2.5 (62%)	2.9 (71%)	<0.001	2.3 (58%)	2.6 (65%)	<0.001
	<45 min	4.1 (100%)	4.1 (100%)	1	3.2 (80%)	3.2 (80%)	1
Tertiary	<15 min	0	0	1	0	0	1
	<30 min	0	0	1	0	0	1
	<45 min	2.0 (49%)	2.7 (66%)	<0.001	1.4 (35%)	1.9(48%)	<0.001

Spatial visualisation of accessibility of healthcare professionals in Nairobi County showed a marked change between time, traffic, and level of healthcare. Facilities offering tertiary healthcare were able to adequately cover the central and northern region of Nairobi while primary health care facilities covered the western and eastern region. Secondary health facilities had a predominantly sub-optimal accessibility ratio in the central region (Figure 14). In less than 30 minutes, the population residing in the peripheries was mainly not able to access healthcare professionals, both during peak and off-peak traffic times.

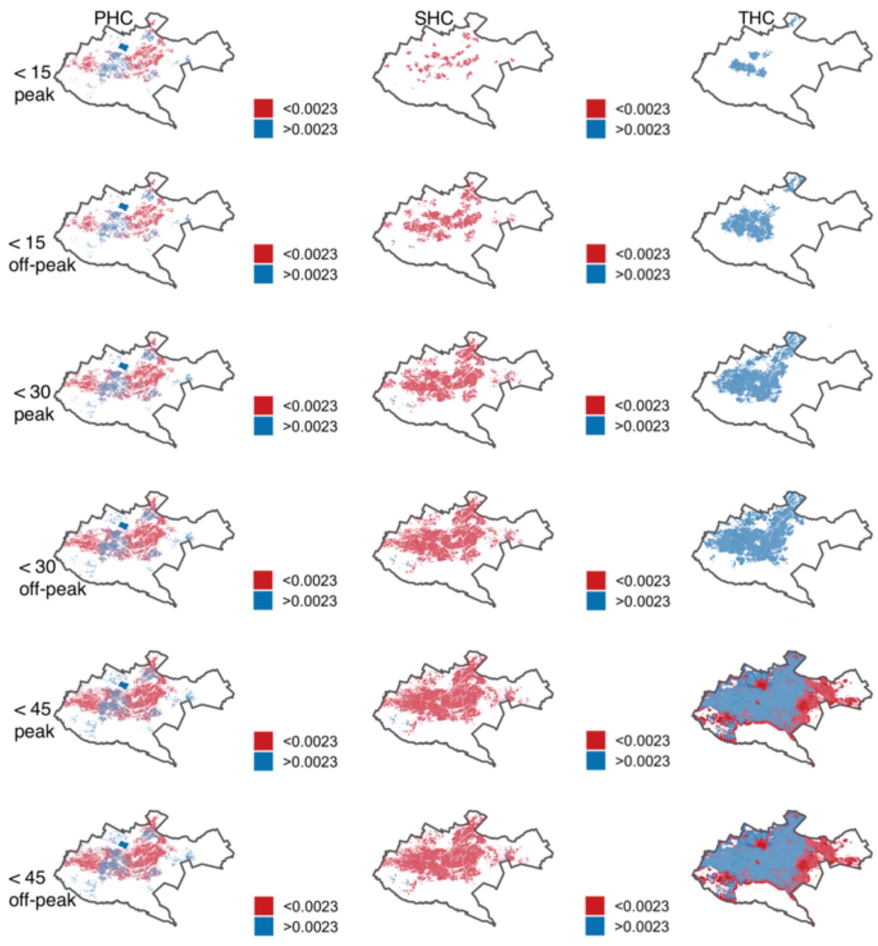


Figure 14: Accessibility index (population: health care professional ratios) by facility tier for primary (PHC), secondary (SHC) and tertiary (THC) health care in Nairobi within 15-, 30- and 45-minutes' drive during peak and off-peak traffic times. The white areas have no accessibility to health care professionals

5.1.3 Discussion

In this study, we use the two-step floating catchment area method to calculate the accessibility of the population to healthcare facilities and professionals, comparing peak and off-peak traffic times while attributing for edge effects. We report that traffic congestion plays a significant role on the proportion of population able to access the different levels of healthcare with more than a third of the population not able to access health facilities within 30 minutes' drive time. Similarly, patterns of inequality are observed where the peripheries are predominantly underserved by inaccessible health facilities and healthcare professionals during periods of traffic congestion. With the population able to access health facilities, a sub-optimal ratio of less than 2.3 healthcare professionals per 1000 people is generally observed in facilities offering primary and secondary healthcare, with edge effects playing a significant role in the ratio.

These results build up on evidence from two studies conducted in Dhaka and Nairobi which reported that traffic congestion had a significant impact on the physical accessibility of health facilities that offer emergency health care, with low accessibility indexes of these health facilities observed in congested areas (Ahmed et al., 2019; Fraser et al., 2020). Transportation barriers to accessing amenities have been associated with delayed access in essential health services (Syed et al., 2013). A study conducted by Chimbindi et al in KwaZulu-Natal reported that the time spent by patients in commuting and at the health facility per month increased the likelihood of financial distress in a patient (Chimbindi et al., 2015). This may be explained by the time spent away from the workplace, affecting the patients' income. To increase adherence to healthcare visits, one of the strategies would be to use traffic variation on physical access of health facilities to plan on the optimal placement of future healthcare facilities offering primary and curative services.

One of the primary goals of achieving the essential universal health coverage to all by 2030, which has the potential of reducing the mortality from non-communicable diseases, is to ensure the majority of patients have access to curative healthcare services and adequate workforce (United Nations, 2015b). However, results from this study showed a sub-optimal shortage in healthcare professionals. Additionally, the WHO has reported sub-optimal shortage of these professionals in developing countries, particularly in sub-Saharan Africa (World Health Organization, 2006). This shortage may be explained by the multiple jobholding of healthcare professionals in developing countries who are mostly employed by government-owned health facilities, but also consult in privately owned hospitals, and also the emigration of healthcare professionals to developed countries (Baughman et al., 2020; Dovlo, 2007). The ageing workforce and the imbalances in the distribution and skill mix composition of healthcare professionals in the different cadre and ownership status of health facilities has also contributed to the shortage in healthcare professionals (Sousa et al., 2014).

A significant change in the sub-optimal ratio of healthcare professionals to population was observed during the implementation of edge effects, with the central regions enjoying relatively better access to health facilities and ratio of population to healthcare professionals. This was in contrast to results from a study in France that observed only minor variation in accessibility of healthcare when edge effects were considered(Gao et al., 2017). This difference in study findings can be explained by the structure of the city and the healthcare utilisation of the population in the periphery in developing regions. Many LMICs have expanded rapidly outwards from a formally planned core, often with limited regulatory oversight or planning (Kingoriah, 1983). This structure has influenced the peripheries as these areas are forgotten during planning and development of basic social services (Woltjer, 2014). One of the coping mechanisms of the peripheries has been utilisation of healthcare services from neighbouring areas which are relatively closer. This was observed in Ghana where residents in the peripheries utilised healthcare services from the neighbouring areas (Dotse-Gborgbortsi et al., 2020). Peripheries should be included when planning the development of cities to ensure there is adequate service provided for all residents in the administrative boundary.

Similar to healthcare, a study conducted in Nairobi, a rapidly urbanising city, reported that more than three quarters of the population in Nairobi was not able to access jobs in the city during peak time, with the population residing in peripheries being highly disadvantaged (Nakamura and Avner, 2021). These findings thus add to evidence that traffic variation plays a significant role in accessibility of services, and a multisectoral collaboration between the ministries of health and transport should be incorporated while optimizing placement of health facilities. The 2-step floating catchment area method should be used in the optimal placement of public amenities and services in congested cities. Specifically, this may be augmented with use of probe traffic data which is available from different commercial sources and with increasing global coverage in rapidly urbanising LMIC cities (Dotse-Gborgbortsi et al., 2018).

One major assumption of this study, which has also been evidenced in previous studies, was the use of the 2SFCA as a key measure of spatial accessibility to healthcare services and professionals using equal accessibility of the population within the catchment area regardless of time taken to the health facility (Tao et al., 2018). An Enhanced Two Step Floating Catchment Area (E2SFCA) method has been proposed to account for this weakness, though a standard distance or time-decaying method is not yet proposed (McGrail and Humphreys, 2009). Another shortfall of the 2SFCA method was the unavailability of a standard metric on the minimum time that one ought to travel while seeking healthcare services and the ratio of healthcare professionals to population, making it difficult to compare study findings from different countries or populations (Langford et al., 2016). UHC, which seeks to ensure that every person should have equitable access to quality healthcare services which are available when needed, should propose a recommended time that should be taken in seeking the different levels of healthcare services. Similarly, a recommended ratio of the cadre of healthcare professionals to population should be proposed, while keeping in mind that the population is not willing to travel longer distances to seek healthcare (McGrail and Humphreys, 2009). Another assumption made in the study was the use of an average number of healthcare professionals to represent all the health facilities per category. The WHO has designed a registry of healthcare professionals with the aim of helping countries track their health workforce per facility (World Health Organization, 2015). However, this data for Kenya was not readily available to allow comprehensive calculation of the accessibility index of the population to the healthcare workers (Wangia and Kandie, 2018). A future study should assess the number of healthcare professionals per health facility and determine the precise ratio between healthcare professionals and the population.

Routing services such as those provided by ESRI currently use historic traffic data to estimate mean journey times at specific times of week and day. From a health services planning perspective, unpredictability in travel times may give rise to missed appointments and healthcare system costs. Routing services that estimate the variance in travel times alongside the mean could thus support future studies of UHC in congested cities (Syed et al., 2013).

5.1.4 Conclusion

We argue that traffic congestion should be incorporated by urban planners and policy makers while planning for healthcare and other services in rapidly urbanising cities. Travel time taken to access a health facility has implications on non-utilisation of healthcare and delayed healthcare. Similarly, ratio of healthcare workforce to the population should be incorporated in planning for healthcare to optimise coverage during peak and off-peak traffic times.

5.2 Spatiotemporal Patterns of Cholera and Associated Risk Factors in Nairobi City

The annual burden of cholera in sub-Saharan Africa (SSA) is estimated at 5.5 million cases respectively, with a case fatality rate of 1.8%(Ali et al., 2015; WHO, 2018). Outbreaks from this epidemic-prone disease have been reported in this region in recent years, with the frequency and size increasing over time (Lessler et al., 2018). Cholera and typhoid are notifiable waterborne diseases, with cholera having relatively fewer cases of clinical misdiagnosis (Ngwu and Agbo, 2003).

Inadequate access to clean drinking water, poor sanitation, low socio-economic status and poor access to health facilities have been highlighted as the dominant risk factors associated with prevalence of this waterborne disease (Richterman et al., 2018). Socio-economic disparity has been reported in access to basic services, type of housing and health outcomes, with residents in urban low income areas bearing the brunt of this inequality (Dos Santos et al., 2017; Zhang, 2016). Many studies on cholera in urban areas in SSA have reported populations living in these urban low income areas to be at higher risk of waterborne diseases (Mutono et al., 2021).

Target 3.3 of the United Nations Sustainable Development Goals aims to end the epidemics associated with waterborne diseases among other priority diseases by 2030 (United Nations, 2015b). One of the critical steps towards eliminating the burden associated with this epidemic-prone disease is to understand and identify spatio-temporal variation and hotspots. Previously, spatial and temporal variation of waterborne diseases or syndromes have been investigated extensively using scan statistics (Alemayehu et al., 2020; Horwood et al., 2014). The studies revealed that hotspots were observed in areas with unclean or inadequate access to water (Alemayehu et al., 2020; Horwood et al., 2014). There have been however few studies on the spatio-temporal high-risk clusters and risk factors of epidemic prone waterborne diseases in urban areas in SSA, which by 2050, will accommodate more than half (55%) of the population in this region (Mutono et al., 2021; UN-DESA, 2014).

Disease surveillance data are required to improve the understanding of the disease burden, detecting outbreaks and hotspot areas and in designing strategies for the control of these infectious diseases. Countries in SSA mostly rely on hospital-based surveillance of diseases of primary concern such as cholera (Fall et al., 2019; WHO and CDC, 2010). This surveillance system integrates both passive and active surveillance of multiple diseases and injuries, providing enhancing the monitoring of a community's health, and any disease outbreaks (Akukwe and Popejoy, 2013). Almost all (87%) countries in SSA use the District Health Information System version 2 (DHIS2), an integrated surveillance system at a national scale to enable reporting of aggregate disease events and occurrences at a facility level (DHIS2, 2020). Similarly, 98% of health facilities in Nairobi, a rapidly urbanising city, are primary healthcare facilities, and almost all the population (95%) is able to access these facilities within a 45-minute period (Mutono et al., 2021). Whilst governments have invested both time and resources to collect and improve availability of reliable data (Dehnavieh et al., 2019), very few studies have used this data to understand the significant high risk areas associated with epidemic-prone waterborne diseases, while linking the data to water sufficiency. This is paramount because per capita monthly water consumption of at least 1500 litres is required to ensure low level of health concern, yet the water distribution process for Nairobi has highlighted that the lower income areas are at risk of insufficient piped water consumption, increasing their risk to waterborne diseases (Mutono et al., 2022).

Nairobi is one of the populous urban areas in SSA with three quarters of its population located in lower-middle and low-income areas of the city (Mutono et al., 2022; UN-Habitat, 2006). Identification of the spatio-temporal variation and hotspots of cholera in this city has not materialised despite reported high burden and recurrent outbreaks of this waterborne disease, and implementation of the Integrated Disease Surveillance and Response (IDSR) strategy in 1998 which has listed cholera among the priority diseases which should be regularly reported (Ali et al., 2015; Mutonga et al., 2013; WHO and CDC, 2010).

Given the paucity of studies at a city scale of hotspots and risk factors of epidemic-prone diseases, the objective of this study is to examine the spatio-temporal high-risk clusters and risk factors associated with cholera in Nairobi.

5.2.1 Materials and Methods

5.2.1.1 Study Area

Similar to the other previous chapters, the study was conducted in Nairobi, which has a population of 4.4 million inhabitants as at 2019 (Kenya National Bureau of Statistics, 2019). By 2020, Nairobi city had 1,042 health facilities registered under the Kenya Medical Practitioners and Dentists Council, with 91%, 9% and <1% of these facilities offering primary, secondary and tertiary healthcare services respectively (Kenya Ministry of Health, 2020). Owing to the physical location of these facilities, at least 95% of Nairobi's population would access a facility within a 45-minute period (Mutono et al., 2021).

5.2.1.2 Data Sources

Confirmed cases: We abstracted monthly data on clinically confirmed cases of cholera in each administrative ward, categorised by age (≤5 years, >5 years) reporting to the healthcare facilities during January 2015 to October 2021 from the Kenya Health Information System (DHIS2). Confirmation of cholera cases is done through laboratory isolation of *Vibrio cholerae* from stool samples (WHO and CDC, 2010).

Population data: We abstracted gridded population data for the 2015-2021 period from WorldPop (WorldPop, 2019) and used the age proportions (≤5 and >5years) to calculate the population in each ward during that period (Kenya National Bureau of Statistics and Society for International Development, 2013). WorldPop uses a random forest dasymetric mapping algorithm to predict populations within 100 x 100 m grid cells. The algorithm uses, among other data, country census, location of water bodies, road networks, settlement built-up areas, night-time lights, landcover, and proximity to urban areas, then employs a built-growth modelling framework to calculate yearly population estimates from consecutive census-driven population estimates (Nieves et al., 2020).

Water and sanitation data: We obtained data on residential categories, mode of water access in the different residential categories and water consumption levels in Nairobi and maps of piped sewerage networks from the Nairobi City Water and Sewerage Company, which was utilised in objective one (Nairobi City Water and Sewerage Company, 2021). Briefly, the residential areas are divided into four categories (low, middle/low-, middle- and high-income areas) based on income, population density and type of housing. The high- and middle-income areas access water mainly through inhouse piped water connection while the middle/low- and low-income areas access this resource through shared public standpipes and water kiosks (water vendors who sell water purchased from the utility company), respectively (Mutono et al., 2022). From our first objective, we observed that on average, the per capita monthly water consumption in high, middle, middle/low and low income areas is 13100, 6200, 1700 and 800 litres respectively (Mutono et al., 2022). In addition, we evidenced that compared to the low-income areas, the higher income (high and middle) areas were six and four times more likely to have water sufficiency, while the lower income (middle/low and low) areas were at risk of water insufficiency.

5.2.1.3 Data analysis

To identify hotspots for cholera, cluster analysis was conducted using SaTScan version 9.6. SaTScan employs a Poisson multivariate regression model to calculate high risk clusters based on a Monte Carlo simulation (Block, 2007). High or low risk clusters are determined by calculating the relative risk *(RR)* for the catchment area of each health facility through space and time, using the observed cases within that ward (c), total number of cases in the data (C) and expected number of cases within the ward $E[c]$ as shown in equation (1).

$$RR = \frac{c/E[c]}{(C-c)/(C)-E(c)} \quad (1)$$

An increased risk was calibrated using a relative risk greater than one and vice versa. Wards that did not have any clinically confirmed cases were assigned a relative risk of zero. Statistically significant clusters were determined and their yearly incidence rate per 100,000 computed.

Clusters that had relatively more observed cases than what was expected were identified as hotspots using their maximum likelihood ratio calculated using the observed cases (c), expected number of cases $E[c]$ and total number of cases $[C]$ as in equation (2).

$$(\frac{c}{E[c]})^{c}(\frac{C-c}{C-E[c]})^{C-c} \quad (2)$$

The excess hazard, which is the ratio of observed to expected cases greater than one, was calculated for each ward. The expected number of cases in each ward that was not at significant risk was derived using the population within the administrative area (p) multiplied by the proportion between the total number of cases (C) and the total population (P) while controlling for climatic season (long rain, short rain, cool dry and hot dry), predominant average per capita water consumption categorisation based on the required minimum litres per person to ensure a reduced level of health concern (<1500 litres, >1500 litres), residential category, mode of piped water access and sanitation system (Figure 15). These covariates were utilised based on previous studies which have reported inadequate access to clean drinking water, poor sanitation and low socio-economic status as some of the dominant risk factors associated with prevalence of waterborne diseases (Richterman et al., 2018).

The utility company's sewerage network data was used as a proxy indicator of sanitation access, since small area statistics from the most recent Kenyan population census have not been released. Households that were within 30 metres of a sewerage network were categorised as having access to safely managed sanitation, or unsafely managed if otherwise (UNICEF and WHO, 2017). The use of sanitation data from the utility company was inferred by a previous study which reported rapidly changing nature of sanitation data collected from the census data, recommending use of administrative data which is regularly updated (Noble et al., 2010).

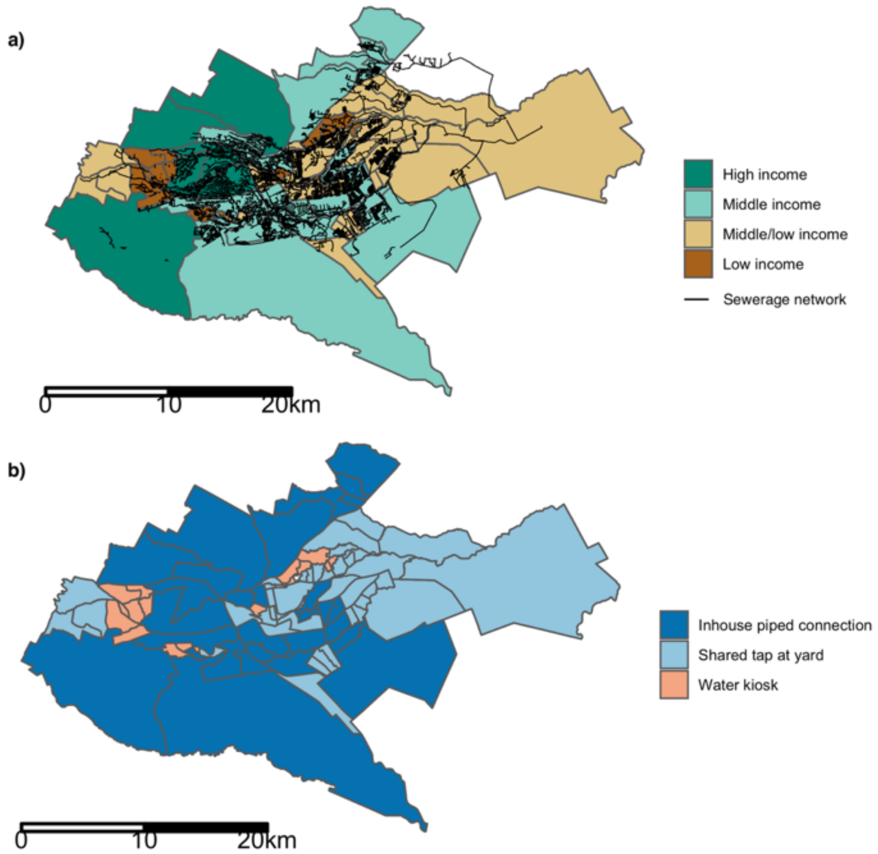


Figure 15: Main residential categories found in the wards together with the sewerage network (a) and methods of water access in the wards (b) in Nairobi City

5.2.2 Results

5.2.2.1 Spatio-temporal Analysis of Cholera Cases

A total of 4,518 cholera cases were reported between January 2015 and October 2021, with children <5 years contributing 369 (8%) of these cases. During this 82-month period, cholera cases in patients <5 years and >5 years were reported in 43 months (52%) and 60 (73%) months respectively. The peak number of cholera cases were reported in July 2017 and August 2019 (Figure 16). On average, Nairobi City experienced a monthly cholera incidence of 12/100,000 persons during outbreak periods, and 1/100,000 persons during non-outbreak periods.

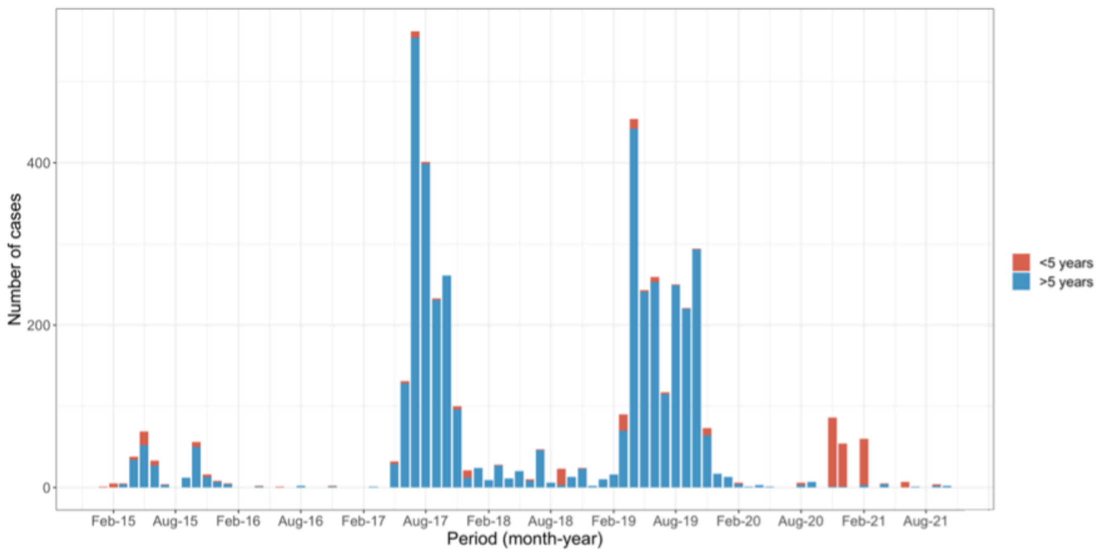


Figure 16**:** Number of cholera cases reported by health facilities in Nairobi City from January 2015-October 2021. Source: Kenya-DHIS2

The average monthly incidence of cholera among children <5 years was predominantly observed in the south-western region, with twenty out of the 85 wards (24%) in Nairobi City reporting an average monthly incidence of at least 1 case per 100,000. Among the population >5 years, the incidence was higher in the south-western and central region, with 25/85 wards (29%) having a monthly incidence of at least one case per 100,000. Less than a third of the wards (12/85, 14%) had a case from both children <5 years and persons >5 years (Figure 17).

Figure 17: Distribution of cholera cases at a ward level reported in health care facilities in Nairobi City between January 2015-October 2021. Shapefile source: Database of Global Administrative Areas

5.2.2.2 Hotspots of Cholera

Three clusters of cholera hotspots among children <5 years were observed during the study period, with the number of observed and expected cases increasing whereas the relative risk reducing over the period. The first geographical cluster was observed over a 34-month period, with a relative risk of 4, translating to 99 cases more than the expected number over the period. The second cluster spanned for 24 months with a relative risk of 2.1 while the third cluster lasted for 12 months, with a relative risk of 1.7 (Table 11). The proportion of wards included in the three clusters were 22% (n=19), 21% (n=18) and 5% (n=4) respectively.

Among individuals >5 years, ten clusters were identified during the study period, with the relative risk ranging from 54.7 – 1.4. The highest relative risks were observed at the beginning (2015-2016) and at the end of the study period (2019-2021), with values of 54.7, 17.2 and 11.5, covering 1% (n=1), 5% (n=4) and 27% (n=23) wards respectively (Table 11).

A list of the wards covered in the high-risk clusters which are categorised by age, the time frame, number of reported and expected cases, together with the relative risk are provided in Table 11.

Table 11: High risk wards and the time frame for each risk, categorised by age (<5 and >5 years)

Ward covered	Time frame	No. of episodes	Expected cases	RR	*P* value
Under 5 years					
Nairobi Central, Ngara, Ziwani/Kariokor, Pumwani,	1/1/2015–31/10/2018	132	33	3.97	<0.001

Pangani, California, Landimawe, Eastleigh North, Mlango Kubwa, Makongeni, Nairobi South, Hospital, Nyayo Highrise, Parklands/Highridge, Eastleigh South, Nairobi West, South C, Airbase, Woodley/Kenyatta Golf Course					
Mowlem, Dandora Area I, Komarock, Dandora Area II, Umoja II, Kariobangi South, Umoja I, Kariobangi North, Korogocho, Kayole Central, Kiamaiko, Dandora Area III, Lower Savannah, Kayole North, Kayole South, Huruma, Lucky Summer, Harambee	1/11/2017 - 31/10/2019	224	104	2.15	<0.001
Pipeline, Kware, Kwa Njenga, Utawala	1/11/2020 - 31/10/2021	344	206	1.67	<0.001
Over 5 years					
Airbase	1/1/2015 – 31/10/2016	24	1	54.65	<0.001
Laini Saba, Lindi, Woodley/Kenyatta Golf Course, Makina, Nyayo Highrise	1/1/2015 – 31/10/2016	300	186	1.61	<0.001
Mihango, Matopeni/Spring Valley, Kayole North, Kayole Central	1/1/2015 – 31/10/2018	56	11	4.92	<0.001

Kwa Njenga, Kware, Pipeline	1/1/2015 – 31/10/2018	216	61	3.52	<0.001
Nairobi Central, Ngara, Ziwani/Kariokor, Pumwani, Pangani, California, Landimawe, Eastleigh North, Mlango Kubwa, Makongeni, Nairobi South	1/11/2016 – 31/10/2017	604	425	1.42	<0.001
Embakasi	1/11/2018 – 31/10/2019	152	67	2.26	<0.001
Nairobi West	1/11/2018 – 31/10/2019	72	22	3.21	<0.001
Kileleshwa	1/11/2018 – 31/10/2020	132	62	2.13	<0.001
Karen, Ngando, Riruta, Mutu-Ini	1/11/2019 – 31/10/2020	32	2	17.18	<0.001
Zimmerman, Githurai, Kahawa, Roysambu, Kasarani, Clay City, Baba Dogo, Lucky Summer, Kahawa West, Korogocho, Mathare North, Dandora Area III, Dandora Area Iv, Dandora Area II, Kariobangi North, Kiamaiko, Dandora Area I, Utalii, Huruma, Mabatini, Mowlem, Njiru, Hospital	1/11/2019– 31/10/2021	160	14	11.49	<0.001

A spatial visualisation of the relative risk shows that the central region had the highest burden of cholera among children below 5 years while the risk among the population above 5 years was observed in the peripheries (Figure 18). similarly, Airbase ward, located in the central region, had the highest relative risk of cholera, both among the population <5 and >5 years.

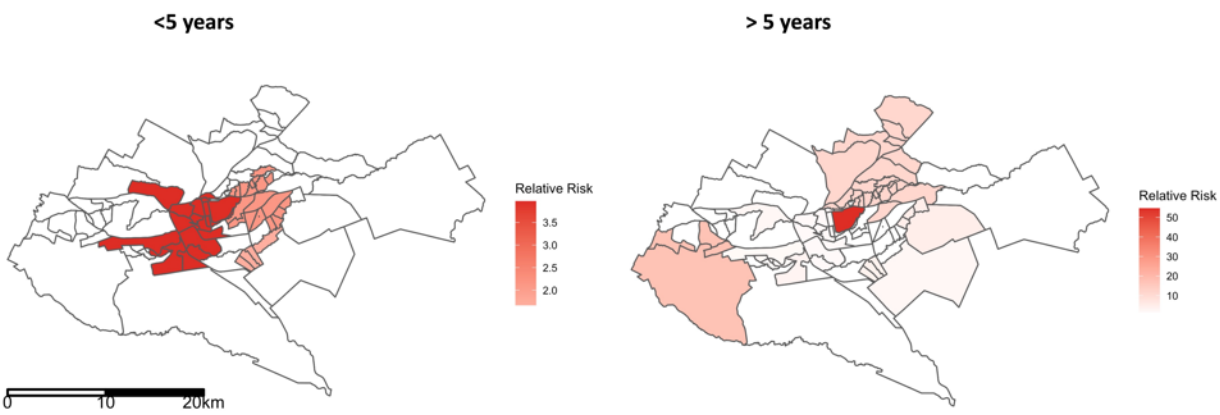


Figure 18: Cholera hotspots identified in Nairobi city between 2015-2020 (black rings). a) water sufficiency (at least 1500 litres per capita average monthly water consumption) for residential areas; b) sanitation systems of residential areas; c) residential categories; d) mode of water access at the residential areas

5.2.2.3 Factors Associated with High-Risk Areas of Cholera

In the population below five years, the predominant high-risk areas, which were assessed using per average capita monthly volumes of water consumption and incidence of cholera cases in the ward administrative boundary, were predominantly in the areas with water consumption of less than 1500 litres per person per month. Similarly, this was also observed in the population above five years, income where households without thirty metres proximity to a piped sewerage network, were at significantly higher risk (Figure 19).

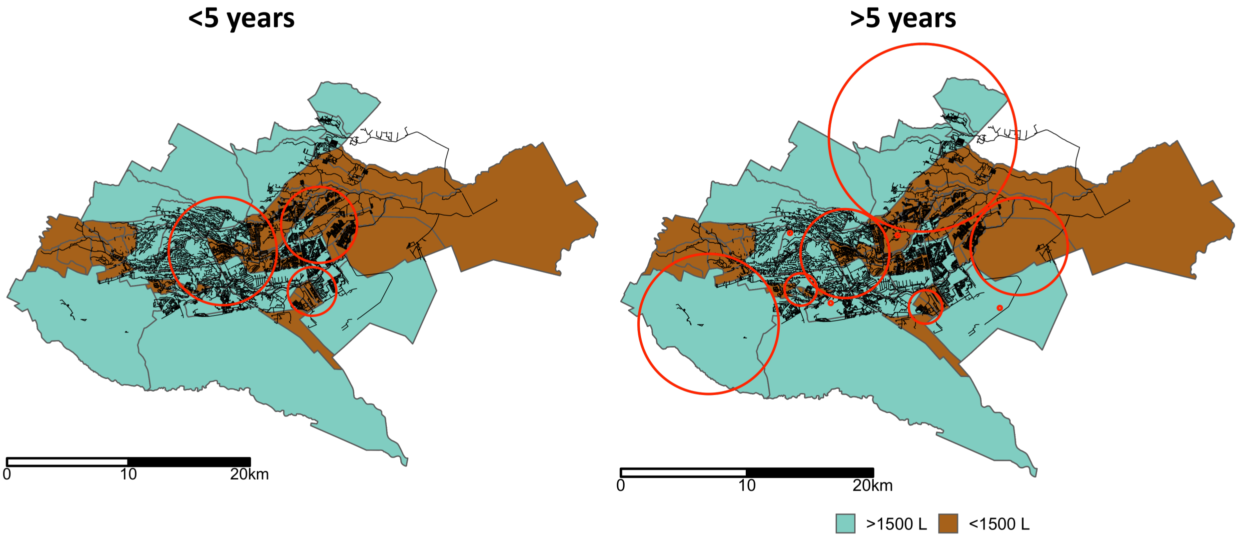


Figure 19: High risk areas (in red) categorised by age, overlaid on the average per capita monthly volumes of water consumed by residents in each ward

5.2.3 Discussion

We analysed spatial variation of cholera hotspots in Nairobi City, while attributing for average per capita water consumption categorisation based on the required minimum litres per person to ensure a reduced level of health concern (<1500 litres, ≥1500 litres), residential category, mode of piped water access and sanitation system. We observed that hotspots of cholera among the population ≤5 and >5 years was associated with per capita monthly water consumption of less than the required 1500 litres and households that were not within a 30 metres proximity to piped sewerage system, residents in lower (middle/low and low) income regions of income and those who accessed piped water through shared taps at yard or water kiosks.

SSA is experiencing a rate of urbanisation which is not commensurate with the development of water and sanitation systems, resulting in insufficiency and inequality in access to basic amenities (Mutono et al., 2021). With more than three quarters of the population in urban areas in SSA residing in middle/low and low income areas, this group is disadvantaged during water structure development plans, pricing and mode of water access, resulting to relatively low volumes of water consumed (Adane et al., 2017; African Development Bank, 2011; Blomkvist and Nilsson, 2017; Mutono et al., 2022; Sakijege, 2019). Volumes of monthly water consumption per person have been reported to be associated with health where individuals with higher per capita monthly volumes of domestic water are prone to lower risk of waterborne diseases (WHO, 2020a). This was similar to our study findings where low levels of water consumption per person per month significantly increased the risk of cholera.

Inequalities in water distribution, which was observed in our previous results, where the higher income areas were consuming sufficient volumes of water whereas the lower income regions were water insufficient has a negative effect on health. This was observed in Harare City where the epicentre of a waterborne disease outbreak, was a region characterised with inadequate water supply (Muti et al., 2014). Water provision plays a fundamental role in urban health, and marginalization of these lower income areas, which are home to three quarters of the urban population, may lead to an increased risk in the disease burden (Hunter et al., 2010; Mutono et al., 2022).

Goal 6 of the Sustainable Development Goals seeks to ensure clean water and sanitation for all(United Nations, 2015b). Improved sanitation, which is categorised as toilet facilities connected to the sewer system, septic tanks, pit latrines and composting toilets, was only accessible to 78% of the urban population in SSA, with nearly a third of this population (32%) sharing these sanitation facilities (UNICEF and WHO, 2019). Similar to our findings, poor sanitation was observed in low income areas in Kisumu, an urban area in Kenya, where toilets are shared between households, while some residents practise unimproved sanitation which includes open defecation (Simiyu et al., 2017). Lack of privacy, insecurity while accessing the toilet and neighbourhood disorganisation are factors that influence open defecation as a choice of sanitation which can be perceived as the best choice from the user's perspective yet this poses a health burden to the community, increasing the risk of waterborne diseases (Mcgranahan, 2015; Winter et al., 2019).

To reduce the disease burden associated with cholera, there is need to improve the quality of life in these low-income areas. According to Winter *et al*, access to sufficient piped water and type of sanitation is significantly associated with health-related quality of life (Winter et al., 2019), and these are essential for countries to meet the targets on the sustainable development goals (Mutyambizi et al., 2020). Increased water management and sanitation strategies have been reported in Durban where improved water access through increased piped water points, reduction in water leakages and gratuitous 200 litres of water provided to households and improved toilets was observed to reduce the cases of diarrhoea (Koenig, 2008).

On the other hand, community participatory process in the design, construction and maintenance of toilets in low income areas in Paris and Durban was observed to decrease cases of waterborne diseases by 30% (Chaudhuri, 2017; Flores et al., 2009; Koenig, 2008). Participatory approach in the environment and health sector have been advocated, where the stakeholders have a sense of ownership in the interventions, resulting to sustainable development (Fuldauer et al., 2019). Good governance would play a pivotal role in this process through ensuring optimum coordination and collaboration across the different stakeholders. This approach is also highlighted in goal 17 of the United Nations Sustainable Development Goals which seeks to ensure partnership for the goals (United Nations, 2015b).

To effectively eliminate the public health burden posed on the low income areas in urban areas who are at high risk, multisectoral collaboration would be required to ensure good health and well-being for all (goal three), provision of adequate clean water and sanitation (goal six), reduction of economic disparities which correlate with access to amenities (goal ten) and ensuring sustainable cities and communities which is possible through participatory planning and management (goal eleven) (United Nations, 2015b). This multisectoral approach in health promotion and public health interventions has been observed in the control and mitigation of endemic and epidemic prone diseases which include rabies and malaria, among others (Gautam et al., 2020; Ranaweera et al., 2020).

One of the limitations of this study was assuming that households would seek health promotion and prevention services from the closest facility offering primary health care services. The use of Kenya DHIS2 data was another study limitation as this is passive surveillance data and bias might result from this data not being population based. Additionally, we assumed that health facilities were correctly diagnosing and promptly reporting cholera cases on a weekly basis in the DHIS2 system. Moreover, we did not correct for the cholera cases that did not seek health care because we made the assumption that cholera was a disease that needed medical attention and in as much as patients postponed visiting the health care facilities immediately the symptoms began, they eventually sought care in these facilities. Future research should conduct a field trial on cholera cases in the community to understand the proportion of patients who develop symptoms of the disease but fail to visit a health facility.

5.2.4 Conclusion

Every individual has a right to adequate amenities which contribute towards quality life. Similarly, equity in water distribution should be enforced to ensure all residential areas have adequate volumes of water required to ensure low level of health outcomes. A multi-sectoral approach between the Ministry of Health and Ministry of water should be utilised where budgets allocated to treating waterborne diseases may be channelled to ensure high risk areas are prioritised in water infrastructure, volumes of water supplied and improved sanitation through piped sewerage connection to reduce the burden associated with cholera in urban areas. This has the potential of actualizing the important role of governance in ensuring sufficient and clean water and sanitation to all.

Chapter Six: Results for Objective Three

6.1 Medium-term Forecasting of Water Demand in Relation to Population Growth in Nairobi City

The provision of safe drinking water is one of the fundamental factors in effectively maintaining good health (Hunter et al., 2010). This is supported in the Health in All Policies (HiAP) approach which highlights the importance of promoting urban health by implementing the United Nations Sustainable Development Goal 6 on water provision and sanitation for all(Ramirez-Rubio et al., 2019). To ensure low levels of health concern, the World Health Organization (WHO) has recommended a monthly consumption of at least 1500 litres per person for domestic purposes during non-outbreak conditions (WHO, 2020a). However, population growth and climate variability have increased pressure on the available water sources and made it strenuous for countries in the global south to achieve the proposed targets (Beard and Mitlin, 2021b; Vairavamoorthy et al., 2008).

In urban sub-Saharan Africa (SSA), piped water has been categorised as the predominant source of clean water (Vivien and Briceno-Garmendia, 2010). Piped water supply and infrastructure layout is not commensurate to the demand in this region, resulting to intermittent water supply (Beard and Mitlin, 2021b; Mafuta et al., 2011). Similarly, inequalities in the piped water distribution process have been observed in the mode of water access and per capita water consumption (Mutono et al., 2022). Residents in the lower income areas access water through shared taps at yard or water kiosks whereas middle and high income areas access the commodity through inhouse connection (Mutono et al., 2022). Similarly, compared to low income areas, the residents in high and middle income areas were six and four times more likely to consume sufficient volumes of water per capita per month (Mutono et al., 2022). These lower income residents who make up three quarters of the urban population (Mutono et al., 2022) were at a higher risk of waterborne diseases, as evidenced through the hotspots for cholera results in the previous chapter.

By 2050, two thirds of the world population projected to reside in urban areas (UN-DESA, 2014). Nairobi, a rapidly urbanising city, has recorded a 4% annual increase in the urban population, which is mainly driven by the lower income population (Mutono et al., 2022). To ensure low levels of health concern are maintained in this urban population, there is need for adequate planning and management to ensure monthly per capita consumption of piped water (WHO, 2020a).

Demand forecasting is one of the critical activities that have been used in planning and management of scarce resources. It is successfully implemented by accounting for time and the factors influencing demand. Time can be measured using either a very short term (hours to two weeks), short term (2 years or less), medium term (up to 10 years) or long term (decades) scale of forecasting while demand can be accounted using demography, climate and price, among others (Billings and Jones, 2008; Lee et al., 2010; Polebitski et al., 2011).

As of 2014, Nairobi was the eighth most populous city in SSA and it is expected to grow into a megacity by 2040 (Bello-Schünemann and Aucoin, 2016). To design a water insufficiency mitigation strategy for the city of Nairobi which ensures adequate quantities of domestic water of at least 1500 litres per person per month, a water demand forecast which accounts for population growth is required. This chapter seeks to answer the following questions: i) What is the projected per capita monthly water consumption in the different residential areas? ii) What are the optimal interventions that would reduce the projected proportion of the population that is at risk of water insufficiency?

6.2 Materials and Methods

6.2.1 Study Setting

As per the previous chapters, this study was conducted in Nairobi City which is the most populous county in Kenya with an estimated population of 4.4 million people and an annual population growth rate of 4% as at 2019 (Kenya National Bureau of Statistics, 2019; World Bank, 2020). Piped water is treated and supplied by Nairobi City Water and Sewerage Company. The water supply in residential areas is influenced by the categories of residential areas which are based on type of housing, population density and level of income (Mutono et al., 2022). Residents in high and middle income areas have a monthly income of above $900 per month whereas the low income areas have $900 and below (Mutono et al., 2022). In addition, 76% of the population residing in Nairobi comprises of the lower income areas (Mutono et al., 2022).

Figure 20 shows the residential area categories and the water distribution network in Nairobi City.

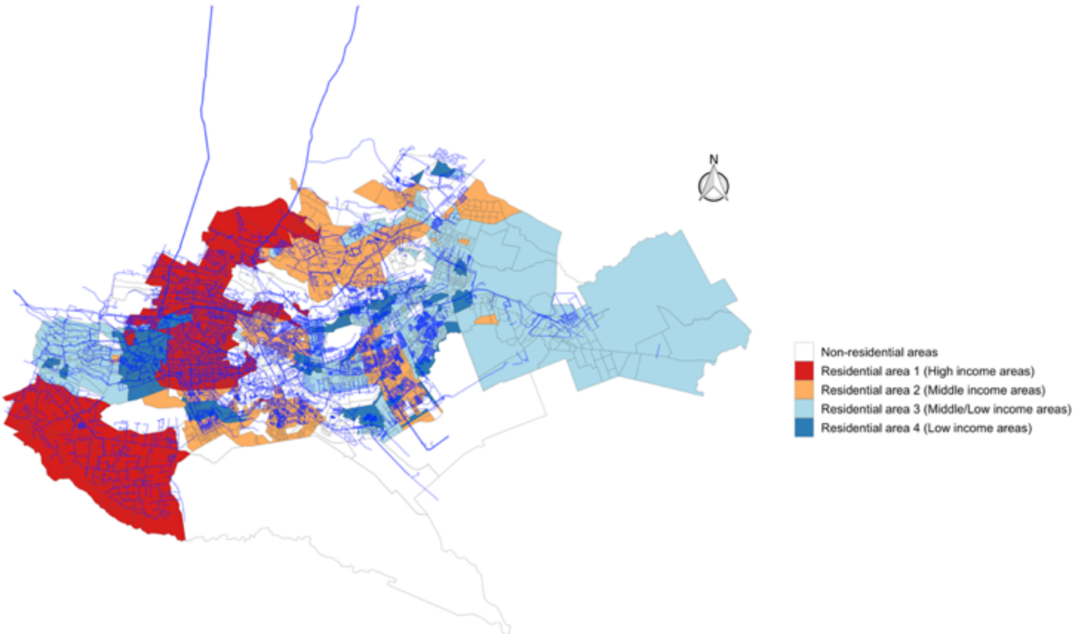


Figure 20: The residential area categories and water distribution network in Nairobi County (Mutono et al., 2022) Shapefile source: GADM

6.2.2 Data Sources

To forecast monthly water needs for Nairobi City from 2019 till 2025, we used ten year data on per capita monthly water consumption and yearly population data for the four different residential areas from 2008 to 2018, together with the estimated non-revenue water for the city, which had been calculated in the first objective (Mutono et al., 2022).

6.2.3 Data Analysis

We employed two models, the exponential smoothing state space model (ETS) and the autoregressive integrated moving average model (ARIMA) which are both used for time series data. In both models, per capita monthly water consumption was used as the response variable and categories of the residential areas were used as the independent variable. The accuracy of the models was evaluated using the mean absolute scaled error and the model with the lowest scaled error was selected.

The penultimate process involved forecasting monthly water consumption per person per month from 2019 to 2025 for the four residential area categories. The volumes of water required by each residential area were calculated using the average annual population growth rate for each of the residential areas. Finally, we analysed the different scenarios that could be implemented to reduce the proportion of the population with insufficient piped water consumption. These scenarios included reduction of non-revenue water to the sectoral benchmark of 25% (Ministry of Environment, 2014), reduced monthly water consumption in high income areas by a third and a half, and investment in a water source with capacity similar to the last constructed main source of piped water for Nairobi City which has a daily transmission of 140 million litres (Thika dam) (Lehner et al., 2011). The model forecasting was calculated using the fable package while the analysis was conducted using R statistical tool (Hyndman, 2021; R Core Team, 2017a). The schematic flow of the study is shown in Figure 21.

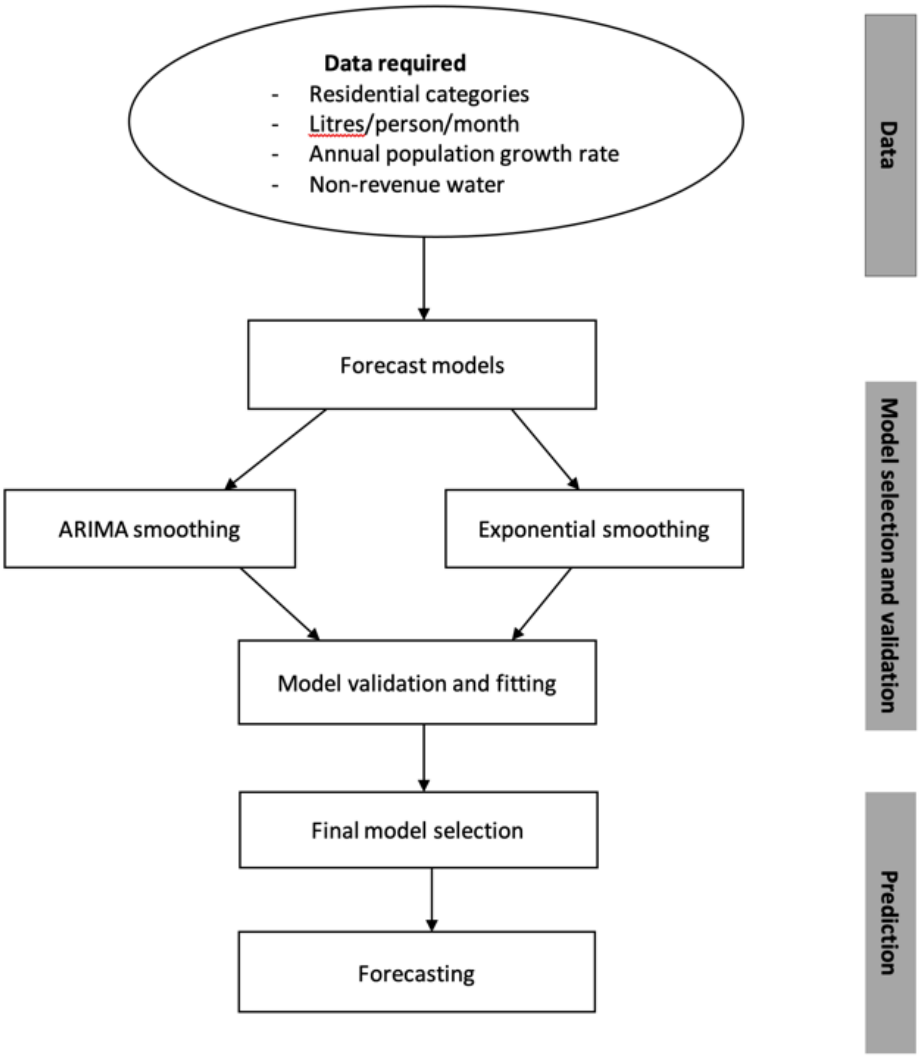


Figure 21: Schema diagram summarising the forecasting process

6.3 Results

6.3.1 Average Population Growth Rate

The highest annual population growth rates were observed in the lower income areas where the low and middle/low-income areas had a rate of 5.7% and 4.3% respectively. The middle-income areas had an annual population growth rate of 3.5% whereas the high-income areas had a declining population growth rate of 1.4%.

6.3.2 Projected Monthly Per Capita Water Consumption

In the period before 2019, the per capita monthly water consumption was observed to be lowest (less than 1500 litres) and erratic in the low-income areas whereas the rest of the residential areas were observed to have a relatively stable declining trend in water consumption. Comparison of the projected monthly water consumption from 2019 to 2025 among the four different residential categories was observed to increase in the middle (47%), middle/low (38%) and high-income areas (21%) whereas a decrease (68%) was observed in the low-income areas (Figure 22).

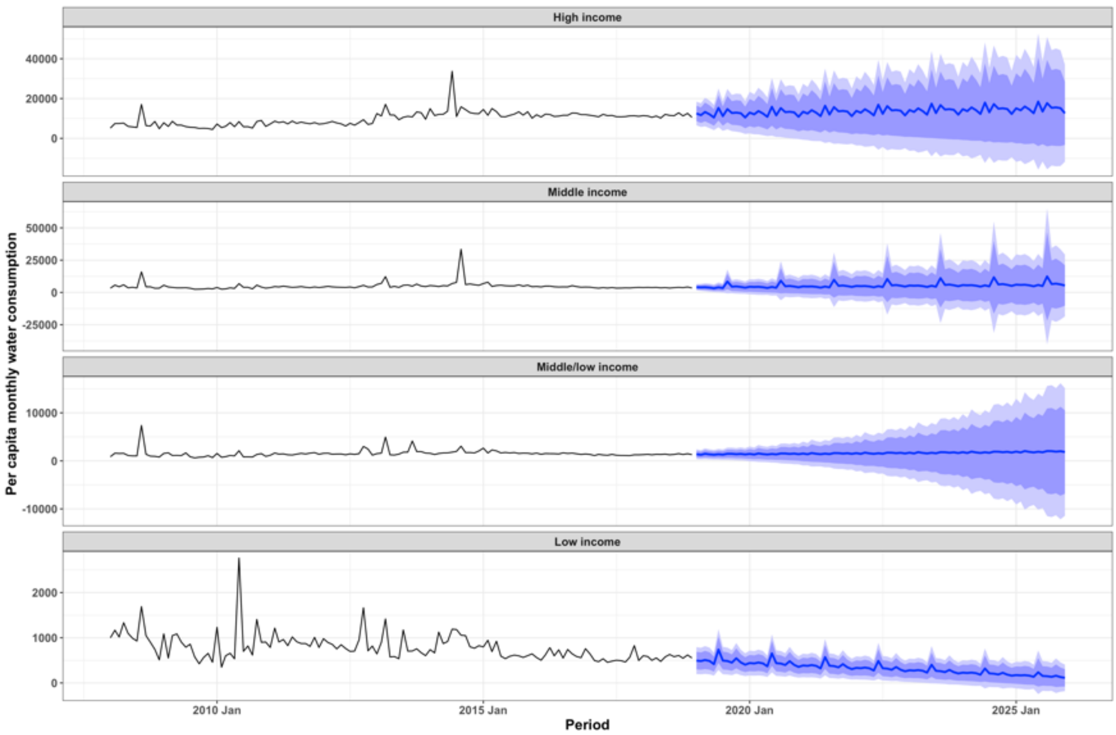


Figure 22: Forecast of per capita monthly water consumption of the four residential areas from 2019 till 2025 using the ETS model

The projected per capita monthly water consumption was negatively correlated to the annual population growth rate where the low-income areas had the highest annual growth rate (5.7%) yet the average monthly water consumption per person was estimated at 157 litres. Furthermore, the high-income areas, which had a projected monthly per capita water consumption estimated at 15,074 litres, had a declining population growth rate (1.4% per year). By 2021, the middle and middle/low-income areas had a projected monthly estimate of 6,357 and 1,908 litres per person and a population growth rate of 4.3% and 3.5% respectively. With the projected water consumption patterns, a total of 14.4 billion litres would be required every month to meet the domestic water demand. Sixty five percent of these volumes of water would be consumed by the high (30%) and middle (35%) income areas whereas the middle/low- and low-income areas would consume 26% and 9% respectively (Table 12).

Table 12: Characteristics of per monthly water consumption and volumes of water required in the four residential areas from 2019 to 2025

Year	High income	Middle income	Middle/low income	Low income
Average monthly per capita				
2019	12,508	4,313	1,378	496
2020	12,935	4,654	1,439	440
2021	13,363	4,994	1,511	383
2022	13,791	5,335	1,592	327
2023	14,219	5,676	1,685	270
2024	14,646	6,016	1,790	213
2025	15,074	6,357	1,908	157
Average volumes of water required per month (in 1000 litres)				
2019	2,923,966	3,408,081	2,538,444	745,922
2020	2,980,847	3,836,773	2,743,062	699,223
2021	3,035,750	4,295,339	2,980,545	643,152
2022	3,088,493	4,787,321	3,249,606	580,249
2023	3,139,126	5,313,855	3,559,131	506,270
2024	3,187,481	5,876,035	3,912,492	422,036
2025	3,234,044	6,477,955	4,315,541	328,716

6.3.2 Scenarios of Water Insufficiency Mitigation Strategies

Comparison of the base scenario, where no improvement would be done to the projected water consumption patterns, and the proposed scenarios showed a substantial change in the proportion of the population in Nairobi that would be at risk of insufficient water consumption. The base scenario would result to 1.9 million of the population (33%) in Nairobi being at risk of water insufficiency whereas reduction of the non-revenue water to 25% and channelling it to the residential areas at risk of water insufficiency would reduce this population to 31% (1,781,258).

Reduction of the per capita monthly water consumption in high income areas by a third and a half over the years was observed to reduce the proportion of the population with risk of water insufficiency to 20% (1,155,865) and 14% (796,574) respectively. Similarly, investment in a large dam similar to the capacity of the last constructed dam was observed to ensure the whole population of Nairobi would have monthly sufficient water consumption of at least 1500 litres per person and have remaining water adequate to serve an extra 6.7 million people. Table 13 shows the different scenarios that would be implemented and the proportion of the total population that would be at risk.

Table 13: Scenarios of water insufficiency mitigation strategies by 2025

	Proportion of population with insufficient water consumption			
Parameters	High income areas	Middle income areas	Middle/low income areas	Low income areas
Scenario in 2019	0	0	1,842,478 (34%)	1,504,301 (34%)
No improvement by 2025	0	0	0	1,874,591 (33%)
Reduction of NRW to 25%	0	0	0	1,781,258 (31%)
Reduced monthly per capita water consumption in high income areas by a third	0	0	0	1,155,865 (20%)
Reduced monthly per capita water consumption in high income areas by a half	0	0	0	796,574 (14%)

Investment in a large dam (transmission of 430 million litres per day)	0	0	0	0

6.4 Discussion

We forecast the domestic water needs in Nairobi for a period of seven years using per capita monthly water consumption of the different residential categories from 2008 to 2018, together with the yearly demography data for the same period. We observed that by 2025, the domestic water demand would increase by 49% to 14.4 billion litres per person per month. The high, middle, and middle/low-income areas would be consuming at least 1500 litres per person per month whereas the low-income areas, which contributed to 33% of the population, would be consuming 157 litres/person/month. We also observed that investment in a large dam equivalent to the transmission of Thika dam, would be equivalent to ensure no one in Nairobi City would consume less than the required 1500 litres for the next 30 years.

In Nairobi, the lower income areas predominantly access piped water through water kiosks and shared taps at yards whereas the higher income areas access this resource through inhouse connections (Mutono et al., 2022). Infrastructure is fundamental in the sustainable development and progress of a city, and it is mainly influenced by income, industrialisation and investment (Li et al., 2017). However, the inadequate investment in water infrastructure has resulted to prioritisation of the middle and high income areas during development which may be explained by the unwillingness of the government to legitimise land tenure for unplanned settlements which are predominantly found in the low income areas (UN-Habitat, 2013).

Similar to Nairobi, a 37%-383% increase in demand has also been predicted in North and South Carolina cities by 2065, with both cities experiencing rapid growth (Sanchez et al., 2020). To ensure cities are prepared for this growth, long-term solutions in water supply which enhance equity should be incorporated in the planning process.

The National water masterplan seeks to ensure at least 2760 litres of water are consumed per person per month in urban areas by 2030. This is supported by proposed investments in water sources that are able to support the increasing population (JICA, 2013). In 2012, the Athi Water Works Development Agency, which is mandated with water and sewerage infrastructure for Nairobi City and its environs, developed a masterplan that entailed construction of a dam (Karimenu II) that would provide water to parts of Nairobi, with a treatment plant capacity of 17 million litres per day. However, the project had faced challenges mainly due to lack of proper collaboration with the national government and the utility company where percentage of the money from the utility companies would be remitted to the National treasury to aid in financing projects (Kenya National Assembly, 2019).

To curb this, multisector transformative collaboration and participation should be enhanced where right investments are prioritised. This would include equitable cost of water which is commensurate to consumption and mode of water access, while also ensuring a low level of health concern. Similarly, the cost of retailing water at the water kiosks should be regulated by the Nairobi City Water and Sewerage company to ensure the residents of low income areas do not end up paying upto nine times more on the cost of water (Monney et al., 2013). Finally, more sustainable water points should be erected in these low income areas to ensure these residents do not end up spending a lot of substantial time fetching water (Mathare Social Justice Centre, 2018).

Some of the study limitations included a focus on domestic water consumption without incorporation commercial water users. This is because residential areas consume 82% of the water supplied in Nairobi City (Mutono et al., 2022). We also assumed that piped water would be the main source of clean water in Nairobi City, as previous studies have highlighted the quality and cost reliability of water from utility companies (Mutono et al., 2021). We did not assess the cost effectiveness of the different scenarios of water insufficiency mitigation strategies. Similarly, we assumed that the per capita water consumption of sufficient volumes would result to low levels of health concern. A future study should be conducted to assess the optimal scenario based on cost and health.

Chapter Seven: Conclusion, General Discussion and Recommendations

7.1 Summary of Important Findings

The important findings from this work were:

a) Inequalities exist in the distribution of piped water; the mode of water access and quantity consumed for populations in different categories of residential areas in Nairobi. High- and middle-income areas accessed water through inhouse connections and had a per capita monthly consumption of 13,087 and 6,240 litres respectively. Middle/low- and low-income areas accessed water through shared taps at yard and water kiosks respectively, with a per capita monthly consumption of 1,697 and 827 litres of water per category.

b) In 45 minutes, at least 85% of the population was able to access health facilities, with a higher ratio of facility to population observed in primary health care. The optimal ratio of 4.45 healthcare workers per 1000 people was lowest secondary health care.

c) Hotspots of cholera among the population were significantly associated with per capita monthly water consumption and proximity to piped sewerage system, residential category of income and type of water access. Residents consuming insufficient volumes of water, in lower income areas and who accessed water either through shared tap at yard (42%) or water kiosks (34%), were at a higher risk of cholera.

d) Comparison of the projected monthly water consumption from 2019 to 2025 among the four different residential categories was observed to increase in the middle (47%), middle/low (38%) and high-income areas (21%) whereas a decrease (68%) was observed in the low-income areas.

e) The growing inequity in water consumption would continue growing and by 2025, low-income areas would still be water insufficient (33% of the total population). The middle/low-income area would only become water sufficient in 2021 (42% of the population) whereas the high and middle income areas, which make up 24% of the population would continue consuming way above the minimum recommended amount of 1500 litres per person per month. By 2025, the high, middle, middle/low- and low-income areas would be consuming an average of 15000, 6000, 2000 and 200 litres per person per month respectively.

f) Mitigation strategies of reducing the non-revenue water to the statutory requirement of 25% would reduce the population at risk of water insufficiency by 2% while investment in an additional water dam with the optimum transmission capacity of 430 million litres per day, would ensure water sufficient in the whole population up until 2035.

Figure 23 shows the schematic diagram summarising the key findings of this thesis research.

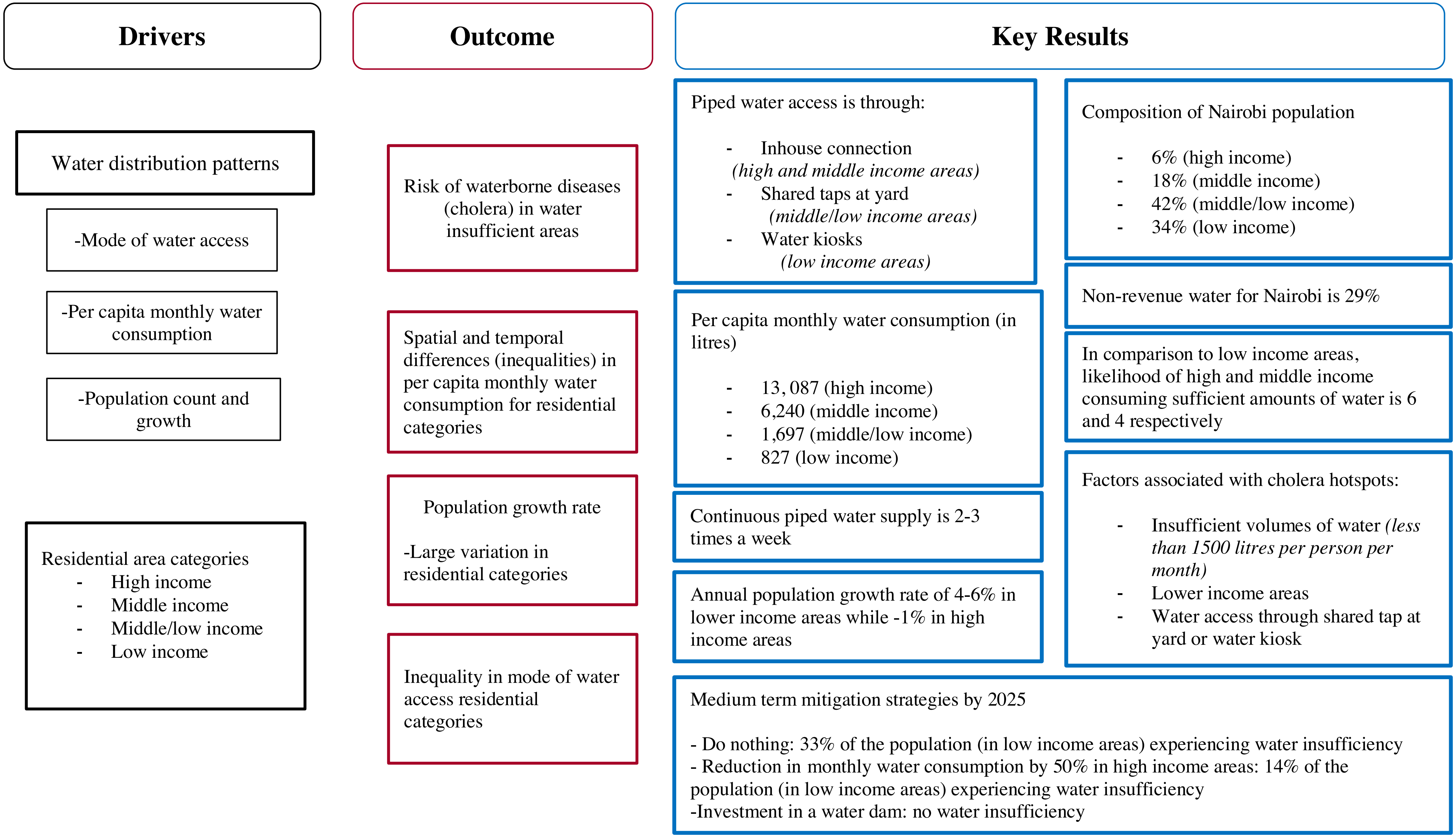


Figure 23: Schematic diagram showing the link between water distribution patterns and health outcomes

7.2 Recommendations

The main recommendations include:

(i) Regularly assess the water needs by using water consumption data to enable guide water allocation and financing of the water gaps. This is also echoed in the OECD principle 5 and 12 that seek to ensure data driven decisions are made to enhance sufficient water distribution and sustainable governance of water (OECD, 2020).

(ii) Ensuring the population is able to access piped water. Investment in water infrastructure which focuses on the lower income areas should increase water access in this population at risk of water insufficiency

(iii) Invest in a large water dam and regulation of underground water- There are plans to invest in a large water resource for urban areas. This resource should be able to sustainably provide water for the future population. Similarly, the borehole services should be regulated to ensure proper abstraction of underground water, and regular testing of the water to ensure it is fit for human consumption as this is the major alternative source of water.

(iv) Reducing inequalities in water consumption. The Joint Monitoring Programme of the SDGs on water, sanitation and health recommend use of coverage gaps, trends and geographic locations as metrics that countries may use to measure inequalities in water, sanitation and hygiene services, while discouraging the use of socio-economic differences (UNICEF and WHO, 2019). The coverage of different locations should be assessed with the country average, and the recommended targets, while the governments work towards closing the gap in inequality. One of the ways the utility company may implement this is by increasing the number of days residents in low and low/middle income areas have access to water and regulating the cost of vended water from water kiosks through implementable policies.

(v) Increase capacity in primary health care by providing resources to ensure outpatient services are predominantly offered in these lower levels and only referral and emergency cases are handled at secondary and tertiary facilities. This will help to decongest the higher-level facilities which only make up 9% of facilities in Nairobi. The Kenya Health Policy has structured this referral system, but implementation is slow. Governance can ensure this is materialised and healthcare resources target the primary health care.

(vi) Multi-sector collaboration is required in the control and elimination of cholera. There should be concerted efforts from both ministries of water and health to ensure sufficient water is accessed in areas marked as hotspots of cholera.

Chapter Eight: References

Abaje, I. B., Ati, O. F., and Ishaya, S. (2009). Nature of Potable Water Supply and Demand in Jema ' a Local Government Area of Kaduna State , Nigeria. *Research Journal of Environmental and Earth Sciences*, *1*(1), 16–21.

Adams, E. A. (2018). Intra-urban inequalities in water access among households in Malawi's informal settlements: Toward pro-poor urban water policies in Africa. *Environmental Development*, *26*(March), 34–42. https://doi.org/10.1016/j.envdev.2018.03.004

Adams, E. A., Sambu, D., and Smiley, S. L. (2019). Urban water supply in Sub-Saharan Africa: historical and emerging policies and institutional arrangements. *International Journal of Water Resources Development*, *35*(2), 240–263. https://doi.org/10.1080/07900627.2017.1423282

Adane, M., Mengistie, B., Medhin, G., Kloos, H., and Mulat, W. (2017). Piped water supply interruptions and acute diarrhea among under-five children in Addis Ababa slums, Ethiopia: A matched case-control study. *PLoS ONE*, *12*(7), 1–19. https://doi.org/10.1371/journal.pone.0181516

Adank, M., van Koppen, B., and Smits, S. (2012). *Guidelines for Planning and Providing Multiple-Use Water Services* (Issue December). https://www.musgroup.net/node/491

African Development Bank. (2011). *The Middle of the Pyramid: Dynamics of the Middle Class in Africa*. *316*(5822), 179d-179d. https://doi.org/10.1126/science.316.5822.179d

African Union. (2015). Agenda 2063: The Africa we want. In *African Union Commission*. https://doi.org/10.18356/8cdc8224-en

Ahmed, S., Adams, A. M., Islam, R., Hasan, S. M., and Panciera, R. (2019). Impact of traffic variability on geographic accessibility to 24/7 emergency healthcare for the urban poor: A GIS study in Dhaka, Bangladesh. *PLoS ONE*, *14*(9), 1–20. https://doi.org/10.1371/journal.pone.0222488

Airey, T. (1992). The impact of road construction on the spatial characteristics of hospital utilization in the Meru district of Kenya. *Social Science and Medicine*, *34*(10), 1135–1146. https://doi.org/10.1016/0277-9536(92)90287-Z

Ajero, C. M., Nwoko, B. E. B., Nwoke, E. A., and Ukaga, C. N. (2008). Human Amoebiasis: Distribution and Burden; and the Nigerian Environment. *International Science Research Journal*, *1*(2), 130–134.

Akinbo, F. O., Okaka, C. E., Omoregie, R., Dearen, T., Leon, E. T., and Xiao, L. (2010). Molecular Characterization of Cryptosporidium spp. in HIV-infected Persons in Benin City, Edo State, Nigeria. *Fooyin Journal of Health Sciences*, *2*(3–4), 85–89. https://doi.org/10.1016/S1877-8607(11)60003-9

Ako, A. A., Nkeng, G. E., and Takem, G. E. E. (2009). Water quality and occurrence of water-borne diseases in the Douala 4th District, Cameroon. *Water Science and Technology*, *59*(12), 2321–2329. https://doi.org/10.2166/wst.2009.268

Akukwe, C., and Popejoy, M. W. (2013). Strengthening health systems. *Global Public Health Policy*, 401–405. https://doi.org/10.12968/ajmw.2010.4.1.46306

Al-Taiar, A., Jaffar, S., Assabri, A., Al-Habori, M., Azazy, A., Al-Gabri, A., Al-Ganadi, M., Attal, B., and Whitty, C. J. M. (2008). Who develops severe malaria? Impact of access to healthcare, socio-economic and environmental factors on children in Yemen: A case-control study. *Tropical Medicine and International Health*, *13*(6), 762–770. https://doi.org/10.1111/j.1365-

3156.2008.02066.x
Aldeyarbi, H. M., Abu El-Ezz, N. M. T., and Karanis, P. (2016). Cryptosporidium and cryptosporidiosis: the African perspective. *Environmental Science and Pollution Research*, *23*(14), 13811–13821. https://doi.org/10.1007/s11356-016-6746-6
Alemayehu, B., Ayele, B. T., Valsangiacomo, C., and Ambelu, A. (2020). Spatiotemporal and hotspot detection of U5-children diarrhea in resource-limited areas of Ethiopia. *Scientific Reports*, *10*(1), 1–11. https://doi.org/10.1038/s41598-020-67623-0
Ali, M., Nelson, A. R., Lopez, A. L., and Sack, D. A. (2015). Updated global burden of cholera in endemic countries. *PLoS Neglected Tropical Diseases*, *9*(6), 1–13. https://doi.org/10.1371/journal.pntd.0003832
Amrose, S., Burt, Z., and Ray, I. (2015). Safe Drinking Water for Low-Income Regions. *Annual Review of Environment and Resources*, *40*(November), 203–231. https://doi.org/10.1146/annurev-environ-031411-091819
Bain, R., Cronk, R., Hossain, R., Bonjour, S., Onda, K., Wright, J., and Yang, H. (2014). Global assessment of exposure to faecal contamination through drinking water based on a systematic review. *Tropical Medicine and International Health*, *19*(8), 917–927. https://doi.org/10.1111/tmi.12334
Baker, K. K., Sow, S. O., Kotloff, K. L., Nataro, J. P., Farag, T. H., Tamboura, B., Doumbia, M., Sanogo, D., Diarra, D., O'Reilly, C. E., Mintz, E., Panchalingam, S., Wu, Y., Blackwelder, W. C., and Levine, M. M. (2013). Quality of piped and stored water in households with children under five years of age enrolled in the Mali site of the Global Enteric Multi-Center Study (GEMS). *American Journal of Tropical Medicine and Hygiene*, *89*(2), 214–222. https://doi.org/10.4269/ajtmh.12-0256
Banerjee, S. G., and Morella, E. (2011). *Africa's Water and Sanitation Infrastructure* (V. Foster and C. Briceño-Garmendia (eds.)). The World Bank. https://doi.org/10.1596/978-0-8213-8457-2
Barzilay, E. J., Aghoghovbia, T. S., Blanton, E. M., Akinpelumi, A. A., Coldiron, M. E., Akinfolayan, O., Adeleye, O. A., LaTrielle, A., Hoekstra, R. M., Gilpin, U., and Quick, R. (2011). Diarrhea prevention in people living with HIV: An evaluation of a point-of-use water quality intervention in Lagos, Nigeria. *AIDS Care - Psychological and Socio-Medical Aspects of AIDS/HIV*, *23*(3), 330–339. https://doi.org/10.1080/09540121.2010.507749
Baughman, R. A., Stanley, B., and Smith, K. E. (2020). Second Job Holding Among Direct Care Workers and Nurses: Implications for COVID-19 Transmission in Long-Term Care. *Medical Care Research and Review*. https://doi.org/10.1177/1077558720974129
Beard, V. A., and Mitlin, D. (2021a). Water access in global South cities: The challenges of intermittency and affordability. *World Development*, *147*, 105625. https://doi.org/10.1016/j.worlddev.2021.105625
Beard, V. A., and Mitlin, D. (2021b). Water access in global South cities: The challenges of intermittency and affordability. *World Development*, *147*, 105625. https://doi.org/10.1016/j.worlddev.2021.105625
Bellaubi, F., and Visscher, J. T. (2014). Water service delivery in Kenya and Ghana: an area-based assessment of water utility performance. *Water International*, *39*(7), 952–968. https://doi.org/10.1080/02508060.2015.985976
Bello-Schünemann, J., and Aucoin, C. (2016). *African urban futures*. *November*.
Billings, R. B., and Jones, C. V. (2008). *Forecasting urban water demand* (2nd ed.). American Water Works Association.

Bivins, A. W., Sumner, T., Kumpel, E., Howard, G., Cumming, O., Ross, I., Nelson, K., and Brown, J. (2017). Estimating Infection Risks and the Global Burden of Diarrheal Disease Attributable to Intermittent Water Supply Using QMRA. *Environmental Science and Technology*, *51*(13), 7542–7551. https://doi.org/10.1021/acs.est.7b01014

Blanton, E., Wilhelm, N., O'Reilly, C., Muhonja, E., Karoki, S., Ope, M., Langat, D., Omolo, J., Wamola, N., Oundo, J., Hoekstra, R., Ayers, T., De Cock, K., Breiman, R., Mintz, E., and Lantagne, D. (2015). A rapid assessment of drinking water quality in informal settlements after a cholera outbreak in Nairobi, Kenya. *Journal of Water and Health*, *13*(3), 714–725. https://doi.org/10.2166/wh.2014.173

Block, R. (2007). Scanning for clusters in space and time: A tutorial review of SaTScan. *Social Science Computer Review*, *25*(2), 272–278. https://doi.org/10.1177/0894439307298562

Blomkvist, P., and Nilsson, D. (2017). On the need for system alignment in large water infrastructure: Understanding infrastructure dynamics in Nairobi, Kenya. *Water Alternatives*, *10*(2), 283–302.

Boakye-Ansah, A. S., Schwartz, K., and Zwarteveen, M. (2019). Unravelling pro-poor water services: What does it mean and why is it so popular? *Journal of Water Sanitation and Hygiene for Development*, *9*(2), 187–197. https://doi.org/10.2166/washdev.2019.086

Brueckner, J. K., Thisse, J. F., and Zenou, Y. (1999). Why is central Paris rich and downtown Detroit poor? An amenity-based theory. *European Economic Review*, *43*(1), 91–107. https://doi.org/10.1016/S0014-2921(98)00019-1

Castro, V., and Morel, A. (2008). Can delegated management help water utilities improve services to informal settlements? *Waterlines*, *27*(4), 289–306. https://doi.org/10.3362/1756-3488.2008.034

Central Bureau of Statistics. (1985). *Economic Survey 1985*.

Cetrulo, T. B., Marques, R. C., Malheiros, T. F., and Cetrulo, N. M. (2020). Monitoring inequality in water access: Challenges for the 2030 Agenda for Sustainable Development. *Science of the Total Environment*, *727*, 138746. https://doi.org/10.1016/j.scitotenv.2020.138746

Chakava, Y., Franceys, R., and Parker, A. (2014). Private boreholes for Nairobi's urban poor: The stop-gap or the solution? *Habitat International*, *43*, 108–116. https://doi.org/10.1016/j.habitatint.2014.01.012

Chaudhuri, I. N. (2017). Community Mobilization for Slum Upgrading through Sanitation in Roma Informal Settlements in the Paris Region. *Frontiers in Public Health*, *5*(August). https://doi.org/10.3389/fpubh.2017.00213

Chaudhuri, S., and Roy, M. (2017). Rural-urban spatial inequality in water and sanitation facilities in India: A cross-sectional study from household to national level. *Applied Geography*, *85*, 27–38. https://doi.org/10.1016/j.apgeog.2017.05.003

Chimbindi, N., Bor, J., Newell, M.-L., Tanser, F., Baltussen, R., Hontelez, J., de Vlas, S. J., Lurie, M., Pillay, D., and Bärnighausen, T. (2015). Time and Money: the true costs of health care utilization for patients receiving 'free' HIV/TB care and treatment in rural KwaZulu-Natal Natsayi. *JAIDS Journal of Acquired Immune Deficiency Syndromes*, *70*(2), e52–e60. https://doi.org/10.1097/QAI.0000000000000728

Christenson, E., Bain, R., Wright, J., Aondoakaa, S., Hossain, R., and Bartram, J. (2014). Examining the influence of urban definition when assessing relative safety of drinking-water in Nigeria. *Science of the Total Environment*, *490*, 301–312. https://doi.org/10.1016/j.scitotenv.2014.05.010

Cobacho, R., Arregui, F., Cabrera, E., and Cabrera, E. (2008). Private Water Storage Tanks: Evaluating Their Inefficiencies. *Water Practice and Technology*, *3*(1), 1–8. https://doi.org/10.2166/wpt.2008.025

Collins, R. M., Spake, R., Brown, K. A., Ogutu, B. O., Smith, D., and Eigenbrod, F. (2020). A systematic map of research exploring the effect of greenspace on mental health. *Landscape and Urban Planning*, *201*(September 2019), 103823. https://doi.org/10.1016/j.landurbplan.2020.103823

Dagdeviren, H., and Robertson, S. A. (2011). Access to water in the slums of sub-Saharan Africa. *Development Policy Review*, *29*(4), 485–505. https://doi.org/10.1111/j.1467-7679.2011.00543.x

Degbey, C., Makoutode, M., Agueh, V., Dramaix, M., and de Brouwer, C. (2011). *Factors associated with the quality of well water and the prevalence of waterborne diseases in the municipality of Abomey-Calavi in Benin*. *21*, 47–55.

Dégbey, C., Makoutode, M., Ouendo, E. M., Fayomi, B., and De Brouwer, C. (2008). The quality of well water in the municipality of Abomey-Calavi in Benin. *Environnement, Risques et Sante*. https://doi.org/10.1684/ers.2008.0158

Dehnavieh, R., Haghdoost, A. A., Khosravi, A., Hoseinabadi, F., Rahimi, H., Poursheikhali, A., Khajehpour, N., Khajeh, Z., Mirshekari, N., Hasani, M., Radmerikhi, S., Haghighi, H., Mehrolhassani, M. H., Kazemi, E., and Aghamohamadi, S. (2019). The District Health Information System (DHIS2): A literature review and meta-synthesis of its strengths and operational challenges based on the experiences of 11 countries. *Health Information Management Journal*, *48*(2), 62–75. https://doi.org/10.1177/1833358318777713

DHIS2. (2020). *DHIS2 in action*. https://www.dhis2.org/inaction

Dill, B., and Crow, B. (2014). The colonial roots of inequality: access to water in urban East Africa. *Water International*, *39*(2), 187–200. https://doi.org/10.1080/02508060.2014.894212

Distefano, T., and Kelly, S. (2017). Are we in deep water ? Water scarcity and its limits to economic growth. *Ecological Economics*, *142*, 130–147. https://doi.org/10.1016/j.ecolecon.2017.06.019

Donkor, E. A., Mazzuchi, T. A., Soyer, R., and Alan Roberson, J. (2014). Urban Water Demand Forecasting: Review of Methods and Models. *Journal of Water Resources Planning and Management*, *140*(2), 146–159. https://doi.org/10.1061/(asce)wr.1943-5452.0000314

Dorice, K., Kabeyene, K., Véronique, B., Nkamjou, S., Gaston, L., and Emmanuel, E. G. (2008). Water supply, sanitation and health risks in Yaounde , Cameroon. *Science And Technology*, *2*(11), 379–386.

Dos Santos, S., Adams, E. A., Neville, G., Wada, Y., de Sherbinin, A., Mullin Bernhardt, E., and Adamo, S. B. (2017). Urban growth and water access in sub-Saharan Africa: Progress, challenges, and emerging research directions. *The Science of the Total Environment*, *607–608*, 497–508. https://doi.org/10.1016/j.scitotenv.2017.06.157

Dos Santos, S., Ouédraogo, F. de C., and Soura, A. B. (2015). Water-related factors and childhood diarrhoea in African informal settlements. A cross-sectional study in Ouagadougou (Burkina Faso). *Journal of Water and Health*, *13*(2), 562–574. https://doi.org/10.2166/wh.2014.115

Dotse-Gborgbortsi, W., Dwomoh, D., Alegana, V., Hill, A., Tatem, A. J., and Wright, J. (2020). The influence of distance and quality on utilisation of birthing services

at health facilities in Eastern Region, Ghana. *BMJ Global Health*, *4*, 1–11. https://doi.org/10.1136/bmjgh-2019-002020
Dotse-Gborgbortsi, W., Wardrop, N., Adewole, A., Thomas, M. L. H., and Wright, J. (2018). A cross-sectional ecological analysis of international and sub-national health inequalities in commercial geospatial resource availability. *International Journal of Health Geographics*, *17*(1), 1–15. https://doi.org/10.1186/s12942-018-0134-z
Dovlo, D. (2007). Migration of nurses from Sub-Saharan Africa: A review of issues and challenges. *Health Services Research*, *42*(3 II), 1373–1388. https://doi.org/10.1111/j.1475-6773.2007.00712.x
Dunne, E. F., Angoran-Bénié, H., Kamelan-Tano, A., Sibailly, T. S., Monga, B. B., Kouadio, L., Roels, T. H., Wiktor, S. Z., Lackritz, E. M., Mintz, E. D., and Luby, S. (2001). Is Drinking Water in Abidjan, Côte d'Ivoire, safe for Infant Formula? *Journal of Acquired Immune Deficiency Syndromes*, *28*, 393–398.
Duran, A., Herbas, D., Reynaga, M., and Butterworth, J. (2004). *Planning for multiple uses of water : Livelihood activities and household water consumption in peri-urban Cochabamba ,. August*, 16–21.
Endris, A. A., Tadesse, M., Alemu, E., Musa, E. O., Abayneh, A., and Assefa, Z. (2019). A case-control study to assess risk factors related to cholera outbreak in addis ababa, ethiopia, july 2016. *Pan African Medical Journal*, *34*(July 2016), 1–12. https://doi.org/10.11604/pamj.2019.34.128.17997
Ercumen, A., Gruber, J. S., and Colford, J. M. (2014). Water distribution system deficiencies and gastrointestinal illness: A systematic review and meta-analysis. *Environmental Health Perspectives*, *122*(7), 651–660. https://doi.org/10.1289/ehp.1306912
Esri. (2020a). *Network analysis coverage*. https://developers.arcgis.com/rest/network/api-reference/network-coverage.htm
Esri. (2020b). *Routing services*. https://enterprise.arcgis.com/en/server/latest/publish-services/windows/what-is-a-routing-service.htm
Essayagh, M., Rhaffouli, A. El, Essayagh, S., and Essayagh, T. (2019). Epidemiology profil of fever typhoid in Meknes (Morocco) 2013–2016. *Revue d'Epidemiologie et de Sante Publique*, *68*(1), 45–49. https://doi.org/10.1016/j.respe.2019.09.006
Fall, I. S., Rajatonirina, S., Yahaya, A. A., Zabulon, Y., Nsubuga, P., Nanyunja, M., Wamala, J., Njuguna, C., Lukoya, C. O., Alemu, W., Kasolo, F. C., and Talisuna, A. O. (2019). Integrated Disease Surveillance and Response (IDSR) strategy: Current status, challenges and perspectives for the future in Africa. *BMJ Global Health*, *4*(4), 1–11. https://doi.org/10.1136/bmjgh-2019-001427
FAO. (2020). Global Forest Resources Assessment 2020. In *FAO Publication*. FAO. https://doi.org/10.4060/ca9825en
Florczyk, A. J., Corbane, C., Ehrlich, D., Freire, S., Kemper, T., Maffenini, L., Melchiorri, M., Politis, P., Schiavina, M., Sabo, F., and Zanchetta, L. (2019). *GHSL Data Package 2019 Public release*. https://doi.org/10.2760/0726
Flores, A., Buckley, C., and Fenner, R. (2009). Selecting sanitation systems for sustainability in developing countries. *Water Science and Technology*, *60*(11), 2973–2982. https://doi.org/10.2166/wst.2009.375
Fraser, M. S., Wachira, B. W., Flaxman, A. D., Lee, A. Y., and Duber, H. C. (2020). Impact of traffic, poverty and facility ownership on travel time to emergency care in Nairobi, Kenya. *African Journal of Emergency Medicine*, *10*(1), 40–45. https://doi.org/10.1016/j.afjem.2019.12.003
Fuldauer, L. I., Ives, M. C., Adshead, D., Thacker, S., and Hall, J. W. (2019).

Participatory planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals. *Journal of Cleaner Production*, *223*, 147–162. https://doi.org/10.1016/j.jclepro.2019.02.269
Ganesan, D., Gupta, S. Sen, and Legros, D. (2020). Cholera surveillance and estimation of burden of cholera. *Vaccine*, *38*, A13–A17. https://doi.org/10.1016/j.vaccine.2019.07.036
Gao, F., Kihal, W., Meur, N. Le, Souris, M., and Deguen, S. (2017). Does the edge effect impact on the measure of spatial accessibility to healthcare providers ? *International Journal of Health Geographics*, 1–16. https://doi.org/10.1186/s12942-017-0119-3
Garrick, D., De Stefano, L., Yu, W., Jorgensen, I., O'Donnell, E., Turley, L., Aguilar-Barajas, I., Dai, X., De Souza Leão, R., Punjabi, B., Schreiner, B., Svensson, J., and Wight, C. (2019). Rural water for thirsty cities: A systematic review of water reallocation from rural to urban regions. *Environmental Research Letters*, *14*(4). https://doi.org/10.1088/1748-9326/ab0db7
Gautam, V., Bhardwaj, P., Saxena, D., Kumar, N., and Dileepan, S. (2020). *Multisectoral approach to achieve canine rabies controlled zone using Intervention Mapping : Preliminary results*. *35*, 1–19. https://doi.org/10.1371/journal.pone.0242937
Gimelli, F. M., Bos, J. J., and Rogers, B. C. (2018). Fostering equity and wellbeing through water: A reinterpretation of the goal of securing access. *World Development*, *104*, 1–9. https://doi.org/10.1016/j.worlddev.2017.10.033
Gleick, P. H. (1998). The human right to water. *Research Handbook on International Water Law*, *1*(1998), 487–503. https://doi.org/10.4337/9781785368080.00028
González-Gómez, F., García-Rubio, M. A., and Guardiola, J. (2011). Why is non-revenue water so high in so many cities? *International Journal of Water Resources Development*, *27*(2), 345–360. https://doi.org/10.1080/07900627.2010.548317
Constitution of Kenya, (2010). www.kenyalaw.org
Kenya Water Act, 164 (2016).
Government of the Republic of Kenya. (2013). *National Water Master Plan 2030*. *October*, 1–281.
Haklay, M., and Weber, P. (2008). OpenStreetMap: User-Generated Street Maps. *IEEE Pervasive Computing*, *7*(4), 12–18. https://doi.org/10.1109/MPRV.2008.80
Heland, F. von, Nyberg, M., Bondesson, A., and Westerberg, P. (2015). The Citizen Field Engineer: Crowdsourced Maintenance of Connected Water Infrastructure. Scenarios for smart and sustainable water futures in Nairobi, Kenya. *Proceedings of EnviroInfo and ICT for Sustainability 2015*, *January*. https://doi.org/10.2991/ict4s-env-15.2015.17
Horwood, P. F., S., K., I., M., M.H., J., B.I., P., R., D., B., R., S., B., A., R., M., U., P.M., S., and A.R., G. (2014). Spatio-temporal epidemiology of the cholera outbreak in Papua New Guinea, 2009-2011. *BMC Infectious Diseases*, *14*(1), 1–10. http://www.embase.com/search/results?subaction=viewrecord&from=export&id=L612367885%0Ahttp://dx.doi.org/10.1186/1471-2334-14-449
Hou, B., Yang, R., Zhan, X., Tian, W., Li, B., Xiao, W., Wang, J., Zhou, Y., and Zhao, Y. (2018). Conceptual framework and computational research of hierarchical residential household water demand. *Water (Switzerland)*, *10*(6), 1–18. https://doi.org/10.3390/w10060696
House-Peters, L. A., and Chang, H. (2011). Urban water demand modeling: Review

of concepts, methods, and organizing principles. *Water Resources Research*, *47*(5). https://doi.org/10.1029/2010WR009624
Hunter, P., MacDonald, A., and Carter, R. (2010). Water supply and health. *PLoS Medicine*, *51*, 1–5. https://doi.org/10.1371/journal.pmed.1000361
Hyndman, R. J. (2021). *CRAN Task View: Time Series Analysis*. https://cloud.r-project.org/web/views/TimeSeries.html
Iddi, S., Akeyo, D., Bagayoko, M., Kiwuwa-Muyingo, S., Chikozho, C., and Kadengye, D. T. (2021). Determinants of transitions in water and sanitation services in two urban slums of Nairobi: A multi-state modeling approach. *Global Epidemiology*, *3*, 100050. https://doi.org/10.1016/j.gloepi.2021.100050
Jain, V., Sharma, A., and Subramanian, L. (2012). Road traffic congestion in the developing world. *Proceedings of the 2nd ACM Symposium on Computing for Development, DEV 2012*. https://doi.org/10.1145/2160601.2160616
JICA. (2013). *The Development of The National Water Master Plan 2030* (Issue October).
Julvez, J., Badé, M. A., Lamotte, M., Campagne, G., Garba, A., Gragnic, G., Bui, A., Kehren, S., Cluzel, F., and Chippaux, J. P. (1998). Les parasitoses intestinales dans l'environnement urbain au Sahel. Étude dans un quartier de Niamey, Niger. *Bulletin de La Societe de Pathologie Exotique*, *91*(5), 424–427.
Kapologwe, N. A., Meara, J. G., Kengia, J. T., Sonda, Y., Gwajima, D., Alidina, S., and Kalolo, A. (2020). Development and upgrading of public primary healthcare facilities with essential surgical services infrastructure: A strategy towards achieving universal health coverage in Tanzania. *BMC Health Services Research*, *20*(1), 1–14. https://doi.org/10.1186/s12913-020-5057-2
Kenya Ministry of Health. (2014). *Kenya Health Policy 2014–2030*.
Kenya Ministry of Health. (2020). *Kenya Master Health Facility List*. http://kmhfl.health.go.ke/#/home
Kenya National Assembly. (2019). *The Report on the Inquiry into the Status of Dams in Kenya*. Government of Kenya.
Kenya National Bureau of Statistics. (2019). 2019 Kenya Population and Housing Census Volume 1: Population by County and Sub-County. In *2019 Kenya Population and Housing Census: Vol. I* (Issue November). https://www.knbs.or.ke/?wpdmpro=2019-kenya-population-and-housing-census-volume-i-population-by-county-and-sub-county
Kenya National Bureau of Statistics, and Society for International Development. (2013). *Exploring Kenya's Inequality: Pulling Apart or Pooling Together?*
Khalil, H., Peters, M., Godfrey, C. M., Mcinerney, P., Soares, C. B., and Parker, D. (2016). An Evidence-Based Approach to Scoping Reviews. *Worldviews on Evidence-Based Nursing*, *13*(2), 118–123. https://doi.org/10.1111/wvn.12144
Kim, J. H., Im, J., Parajulee, P., Holm, M., Cruz Espinoza, L. M., Poudyal, N., Mogeni, O. D., and Marks, F. (2019). A Systematic Review of Typhoid Fever Occurrence in Africa. *Clinical Infectious Diseases*, *69*(Suppl 6), S492–S498. https://doi.org/10.1093/cid/ciz525
Kingoriah, G. K. (1983). The causes of Nairobi's city structure. *Ekistics*, *50*(301), 246–254.
Kirigia, J., Gbary, A., Nyoni, J., Seddoh, A., Seddoh, A., and Muthuri, L. (2008). The cost of health-related brain drain to the WHO African Region. *African Journal of Health Sciences*, *13*(3), 1–12. https://doi.org/10.4314/ajhs.v13i3.30830
Koenig, R. (2008). Durban's poor get water services long denied. *Science (New York, N.Y.)*, *319*(5864), 744–745. https://doi.org/10.1126/science.319.5864.744

Kone-Coulibaly, A., Tshimanga, M., Shambira, G., Gombe, N. T., Chadambuka, A., Chonzi, P., and Mungofa, S. (2010). Risk factors associated with cholera in Harare City, Zimbabwe, 2008. *East African Journal of Public Health*, *7*(4), 311–317. https://doi.org/10.4314/eajph.v7i4.64754

Kruk, M. E., Gage, A. D., Joseph, N. T., Danaei, G., García-Saisó, S., and Salomon, J. A. (2018). Mortality due to low-quality health systems in the universal health coverage era: a systematic analysis of amenable deaths in 137 countries. *The Lancet*, *392*(10160), 2203–2212. https://doi.org/10.1016/S0140-6736(18)31668-4

Kuupiel, D., Adu, K. M., Bawontuo, V., Tabong, P. T. N., Adogboba, D. A., and Mashamba-Thompson, T. P. (2020). Geographical access to point-of-care testing for hypertensive disorders of pregnancy as an integral part of maternal healthcare in Ghana. *BMC Pregnancy and Childbirth*, *20*(1), 1–9. https://doi.org/10.1186/s12884-020-03441-6

Kyessi, A. G. (2005). Community-based urban water management in fringe neighbourhoods: The case of Dar es Salaam, Tanzania. *Habitat International*, *29*(1), 1–25. https://doi.org/10.1016/S0197-3975(03)00059-6

Landford, J., and Nunn, M. (2012). Good governance in “one health” approaches. *Revue Scientifique et Technique (International Office of Epizootics)*, *31*(2), 561–575. https://pubmed.ncbi.nlm.nih.gov/23413734

Langford, M., Higgs, G., and Fry, R. (2016). Multi-modal two-step floating catchment area analysis of primary health care accessibility. *Health and Place*, *38*, 70–81. https://doi.org/10.1016/j.healthplace.2015.11.007

Lê, S., Josse, J., and Husson, F. (2008). FactoMineR: An R package for multivariate analysis. *Journal of Statistical Software*, *25*(1), 1–18. https://doi.org/10.18637/jss.v025.i01

Ledant, M. (2013). Water in Nairobi: Unveiling inequalities and its causes. *Les Cahiers d’Outre-Mer*, *66*(263), 335–348. https://doi.org/10.4000/com.6951

Lee, S.-J., Wentz, E. A., and Gober, P. (2010). *Space – time forecasting using soft geostatistics : a case study in forecasting municipal water demand for Phoenix , Arizona*. 283–295. https://doi.org/10.1007/s00477-009-0317-z

Lehner, B., Liermann, C. R., Revenga, C., Vörömsmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N., and Wisser, D. (2011). High-resolution mapping of the world’s reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494–502. https://doi.org/10.1890/100125

Lessler, J., Moore, S. M., Luquero, F. J., McKay, H. S., Grais, R., Henkens, M., Mengel, M., Dunoyer, J., M’bangombe, M., Lee, E. C., Djingarey, M. H., Sudre, B., Bompangue, D., Fraser, R. S. M., Abubakar, A., Perea, W., Legros, D., and Azman, A. S. (2018). Mapping the burden of cholera in sub-Saharan Africa and implications for control: an analysis of data across geographical scales. *The Lancet*, *391*(10133), 1908–1915. https://doi.org/10.1016/S0140-6736(17)33050-7

Levine, M. M., Nasrin, D., Acácio, S., Bassat, Q., Powell, H., Tennant, S. M., Sow, S. O., Sur, D., Zaidi, A. K. M., Faruque, A. S. G., Hossain, M. J., Alonso, P. L., Breiman, R. F., O’Reilly, C. E., Mintz, E. D., Omore, R., Ochieng, J. B., Oundo, J. O., Tamboura, B., … Kotloff, K. L. (2020). Diarrhoeal disease and subsequent risk of death in infants and children residing in low-income and middle-income countries: analysis of the GEMS case-control study and 12-month GEMS-1A follow-on study. *The Lancet Global Health*, *8*(2), e204–e214.

https://doi.org/10.1016/S2214-109X(19)30541-8
Levy, K., Woster, A. P., Goldstein, R. S., and Carlton, E. J. (2016). Untangling the Impacts of Climate Change on Waterborne Diseases: A Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought. *Environmental Science and Technology*, *50*(10), 4905–4922. https://doi.org/10.1021/acs.est.5b06186
Li, Y., Zheng, J., Li, F., Jin, X., and Xu, C. (2017). Correction: Assessment of municipal infrastructure development and its critical influencing factors in urban China: A FA and STIRPAT approach. *PLoS ONE*, *12*(12), 1–14. https://doi.org/10.1371/journal.pone.0189530
Luo, W., and Qi, Y. (2009). An enhanced two-step floating catchment area (E2SFCA) method for measuring spatial accessibility to primary care physicians. *Health and Place*. https://doi.org/10.1016/j.healthplace.2009.06.002
Machdar, E., van der Steen, N. P., Raschid-Sally, L., and Lens, P. N. L. (2013). Application of Quantitative Microbial Risk Assessment to analyze the public health risk from poor drinking water quality in a low income area in Accra, Ghana. *Science of the Total Environment*, *449*, 134–142. https://doi.org/10.1016/j.scitotenv.2013.01.048
Mafuta, C., Formo, R. K., Nellemann, C., and Li, F. (2011). *Green Hills, Blue Cities: An Ecosystem approach to Water Resources Management for African Cities. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal*.
Maina, J., Ouma, P. O., Macharia, P. M., Alegana, V. A., Mitto, B., Fall, I. S., Noor, A. M., Snow, R. W., and Okiro, E. A. (2019). A spatial database of health facilities managed by the public health sector in sub Saharan Africa. *Scientific Data*, *6*(1), 1–8. https://doi.org/10.1038/s41597-019-0142-2
Majuru, B., Suhrcke, M., and Hunter, P. R. (2016). How do households respond to unreliable water supplies? a systematic review. *International Journal of Environmental Research and Public Health*, *13*(12). https://doi.org/10.3390/ijerph13121222
Malakar, K., Mishra, T., and Patwardhan, A. (2018). Inequality in water supply in India: an assessment using the Gini and Theil indices. *Environment, Development and Sustainability*, *20*(2), 841–864. https://doi.org/10.1007/s10668-017-9913-0
Manya, A., Braa, J., Øverland, L., Titlestad, O., Mumo, J., and Nzioka, C. (2012). National Roll Out of District Health Information Software (DHIS 2) in Kenya, 2011–Central Server and Cloud Based Infrastructure. *IST-Africa 2012*, 1–9.
Marchello, C. S., Hong, C. Y., and Crump, J. A. (2019). Global typhoid fever incidence: A systematic review and meta-analysis. *Clinical Infectious Diseases*, *68*(Suppl 2), S105–S116. https://doi.org/10.1093/cid/ciy1094
Maryati, S., and Humaira, A. N. S. (2015). Increasing the Infrastructure Access of Low-Income People in Peri-Urban of Bandung Metropolitan Area. *International Journal of Built Environment and Sustainability*, *2*(3), 219–226. https://doi.org/10.11113/ijbes.v2.n3.84
Masaba, B. B., Moturi, J. K., Taiswa, J., and Mmusi-Phetoe, R. M. (2020). Devolution of healthcare system in Kenya: progress and challenges. *Public Health*, *189*, 135–140. https://doi.org/10.1016/j.puhe.2020.10.001
Mathare Social Justice Centre. (2018). *Maji ni uhai maji ni haki: Eastlands residentis demand their right to water, a participatory report*. 1–38.
Mcdonald, R. I., Weber, K., Padowski, J., Flo, M., Schneider, C., Green, P. A.,

Gleeson, T., Eckman, S., Montgomery, M., Lehner, B., Balk, D., and Boucher, T. (2014). *Water on an urban planet : Urbanization and the reach of urban water infrastructure*. *27*, 96–105. https://doi.org/10.1016/j.gloenvcha.2014.04.022

McGrail, M. R. (2012). Spatial accessibility of primary health care utilising the two step floating catchment area method: An assessment of recent improvements. *International Journal of Health Geographics*, *11*, 1–12. https://doi.org/10.1186/1476-072X-11-50

McGrail, M. R., and Humphreys, J. S. (2009). Measuring spatial accessibility to primary care in rural areas: Improving the effectiveness of the two-step floating catchment area method. *Applied Geography*, *29*(4), 533–541. https://doi.org/10.1016/j.apgeog.2008.12.003

Mcgranahan, G. (2015). Realizing the Right to Sanitation in Deprived Urban Communities : Meeting the Challenges of Collective Action , Coproduction, Affordability and Housing Tenure. *World Development*, *68*, 242–253. https://doi.org/10.1016/j.worlddev.2014.12.008

Mezue, K., Edwards, P., Nsofor, I., Goha, A., Anya, I., Madu, K., Baugh, D., Nunura, F., Gaulton, G., and Madu, E. (2020). Sub-saharan africa tackleS COViD-19: Challenges and opportunities. *Ethnicity and Disease*, *30*(4), 693–694. https://doi.org/10.18865/ED.30.4.693

Ministry of Environment, W. and N. R. (2014). *Standards for Non-Revenue Water Management in Kenya*.

Mitlin, D., Beard, V. A., Satterthwaite, D., and Du, J. (2019). Unaffordable and Undrinkable: Rethinking Urban Water Access in the Global South. *World Resources Institute*, 1–59. https://www.wri.org/wri-citiesforall/publication/unaffordable-and-undrinkable-rethinking-urban-water-access-global-south%0Ahttps://www.wri.org/wri-citiesforall/cities-all

Monney, I., Buamah, R., Odai, S., Awuah, E., and Nyenje, P. M. (2013). Evaluating Access to Potable Water and Basic Sanitation in Ghana's Largest Urban Slum Community: Old Fadama, Accra. *Journal of Environment and Earth Science*, *3*(11), 72–80. http://iiste.org/Journals/index.php/JEES/article/view/8254

Muti, M., Gombe, N., Tshimanga, M., Takundwa, L., Bangure, D., Mungofa, S., and Chonzi, P. (2014). Typhoid outbreak investigation in Dzivaresekwa, suburb of Harare City, Zimbabwe, 2011. *Pan African Medical Journal*, *18*, 1–7. https://doi.org/10.11604/pamj.2014.18.309.4288

Mutonga, D., Langat, D., Mwangi, D., Tonui, J., Njeru, M., Abade, A., Irura, Z., Njeru, I., and Dahlke, M. (2013). National surveillance data on the epidemiology of cholera in Kenya, 1997-2010. *Journal of Infectious Diseases*, *208*(SUPPL. 1), 55–61. https://doi.org/10.1093/infdis/jit201

Mutono, N., Wright, J. A., Mutembei, H., Muema, J., Thomas, M. L. ., Mutunga, M., and Thumbi, S. M. (2021). The nexus between improved water supply and water-borne diseases in urban areas in Africa: a scoping review. *AAS Open Research*, *4*, 27. https://doi.org/10.12688/aasopenres.13225.1

Mutono, N., Wright, J. A., Mutunga, M., Mutembei, H., and Thumbi, S. (2021). Impact of Traffic Congestion on Spatial Access to Healthcare Services in Nairobi : an ecological study. *Research Square (Preprint)*, 1–21.

Mutono, N., Wright, J., Mutembei, H., Muema, J., Thomas, M., Mutunga, M., and Thumbi, S. M. (2020). The nexus between improved water supply and water-borne diseases in urban areas in Africa: a scoping review protocol. *AAS Open Research*, *3*, 12. https://doi.org/10.12688/aasopenres.13063.2

Mutono, N., Wright, J., Mutembei, H., and Thumbi, S. M. (2022). Spatio-temporal patterns of domestic water distribution, consumption and sufficiency: Neighbourhood inequalities in Nairobi, Kenya. *Habitat International*, *119*(November 2021), 102476. https://doi.org/10.1016/j.habitatint.2021.102476

Mutyambizi, C., Mokhele, T., Ndinda, C., and Hongoro, C. (2020). Access to and satisfaction with basic services in informal settlements: Results from a baseline assessment survey. *International Journal of Environmental Research and Public Health*, *17*(12), 1–21. https://doi.org/10.3390/ijerph17124400

Mwangi, E., Wetterhall, F., Dutra, E., Di Giuseppe, F., and Pappenberger, F. (2014). Forecasting droughts in East Africa. *Hydrology and Earth System Sciences*, *18*(2), 611–620. https://doi.org/10.5194/hess-18-611-2014

Nairobi City Commission. (1985). *Third Nairobi Water Supply project: Population and Water ddemand projections for Nairobi*.

Nairobi City County. (2014). *The Project on Integrated Urban Development Master Plan for the City of Nairobi in the Republic of Kenya*. http://www.kpda.or.ke/documents/Nairobi Integarted Urban Development Master Plan.pdf

Nairobi City County. (2020). *Nairobi City county Government Action Plan:2021-2022*.

Nairobi City Water and Sewerage Company. (2021). *Nairobi City Water and Sewerage Company*. https://www.nairobiwater.co.ke

Nakamura, S., and Avner, P. (2021). Spatial distributions of job accessibility, housing rents, and poverty: The case of Nairobi. *Journal of Housing Economics*, *51*(December 2020), 101743. https://doi.org/10.1016/j.jhe.2020.101743

National Coordinating Agency for Population and Development, Ministry of Medical Services, Ministry of Public Health and Sanitation, Kenya National Bureau of Statistics, and ICF Macro. (2011). Kenya Service Provision Assessment Survey 2010. In *Kenya Service Provision Assessment Survey*. https://esaro.unfpa.org/sites/default/files/pub-pdf/Kenya Service Provision Assessment Survey 2010.pdf%0Ahttp://dhsprogram.com/pubs/pdf/SPA17/SPA17.pdf

Navab-Daneshmand, T., Friedrich, M. N. D., Gächter, M., Montealegre, M. C., Mlambo, L. S., Nhiwatiwa, T., Mosler, H. J., and Julian, T. R. (2018). Escherichia coli contamination across multiple environmental compartments (soil, hands, drinking water, and handwashing water) in urban Harare: Correlations and risk factors. *American Journal of Tropical Medicine and Hygiene*, *98*(3), 803–813. https://doi.org/10.4269/ajtmh.17-0521

Nayebare, S. R., Wilson, L. R., Carpenter, D. O., Dziewulski, D. M., and Kannan, K. (2014). A review of potable water accessibility and sustainability issues in developing countries - Case study of Uganda. *Reviews on Environmental Health*, *29*(4), 363–378. https://doi.org/10.1515/reveh-2013-0019

Ngwu, B. A., and Agbo, J. A. (2003). Typhoid fever: clinical diagnosis versus laboratory confirmation. *Nigerian Journal of Medicine : Journal of the National Association of Resident Doctors of Nigeria*, *12*(4), 187–192.

Nieves, J. J., Sorichetta, A., Linard, C., Bondarenko, M., Steele, J. E., Stevens, F. R., Gaughan, A. E., Carioli, A., Clarke, D. J., Esch, T., and Tatem, A. J. (2020). Annually modelling built-settlements between remotely-sensed observations using relative changes in subnational populations and lights at night. *Computers, Environment and Urban Systems*, *80*(November 2019), 101444. https://doi.org/10.1016/j.compenvurbsys.2019.101444

Nilsson, D. (2016). The Unseeing State: How Ideals of Modernity Have Undermined Innovation in Africa's Urban Water Systems. *NTM International Journal of History and Ethics of Natural Sciences, Technology and Medicine*, *24*(4), 481–510. https://doi.org/10.1007/s00048-017-0160-0

Nkhuwa, D. C. W. (2003). Human activities and threats of chronic epidemics in a fragile geologic environment. *Physics and Chemistry of the Earth*, *28*(20–27), 1139–1145. https://doi.org/10.1016/j.pce.2003.08.035

Noble, M., Barnes, H., Wright, G., and Roberts, B. (2010). Small Area Indices of Multiple Deprivation in South Africa. *Social Indicators Research*, *95*(2), 281–297. https://doi.org/10.1007/s11205-009-9460-7

OECD. (2020). OECD Principles on Water Governance. *OECD Principles on Water Governance*, *June*. https://doi.org/10.4324/9780429448058

Oguntoke, O., Aboderin, O. J., and Bankole, A. M. (2009). Association of water-borne diseases morbidity pattern and water quality in parts of Ibadan City, Nigeria. *Tanzania Journal of Health Research*, *11*(4), 189–195. https://doi.org/10.4314/thrb.v11i4.50174

Olima, W. H. A., and K'Akumu, O. A. (1999). The problems of project implementation: A post-mortem study of Thika Dam project, Kenya. *Habitat International*, *23*(4), 467–479. https://doi.org/10.1016/S0197-3975(99)00021-1

Ouma, P. O., Maina, J., Thuranira, P. N., Macharia, P. M., Alegana, V. A., English, M., Okiro, E. A., and Snow, R. W. (2018). Access to emergency hospital care provided by the public sector in sub-Saharan Africa in 2015: a geocoded inventory and spatial analysis. *The Lancet Global Health*, *6*(3), e342–e350. https://doi.org/10.1016/S2214-109X(17)30488-6

Sow., S., B.M., D., M., M.-B., A., S., C.T., N., N.M., D., D., B., S., B., and A.M., C.-S. (1999). The 1995-1996 cholera epidemics in Dakar (Senegal). *Medecine et Maladies Infectieuses*.

Peters, D. H., Garg, A., Bloom, G., Walker, D. G., Brieger, W. R., and Hafizur Rahman, M. (2008). Poverty and access to health care in developing countries. *Annals of the New York Academy of Sciences*, *1136*, 161–171. https://doi.org/10.1196/annals.1425.011

Peters, M., Godfrey, C., McInerney, P., Munn, Z., Tricco, A., and Khalil, H. (2020). *Chapter 11:Scoping Reviews (2020 version), Joanna Briggs Institute Reviewer's Manual*. Aromataris E, Munn Z (Editors). https://reviewersmanual.joannabriggs.org/

Pham, M. T., Rajić, A., Greig, J. D., Sargeant, J. M., Papadopoulos, A., and Mcewen, S. A. (2014). A scoping review of scoping reviews: Advancing the approach and enhancing the consistency. *Research Synthesis Methods*, *5*(4), 371–385. https://doi.org/10.1002/jrsm.1123

Plummer, R., de Loë, R., and Armitage, D. (2012). A Systematic Review of Water Vulnerability Assessment Tools. *Water Resources Management*, *26*(15), 4327–4346. https://doi.org/10.1007/s11269-012-0147-5

Polebitski, A. S., Palmer, R. N., and Waddell, P. (2011). *Evaluating Water Demands under Climate Change and Transitions in the Urban Environment*. *137*(June), 249–257. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000112

QGIS Development Team. (2016). QGIS Geographic Information System. In *Open Source Geospatial Foundation Project*.

R Core Team. (2017a). *R: A language and environment for statistical computing. http://www.R-project.org/.* R Foundation for Statistical Computing, Vienna, Austria. https://doi.org/10.1007/978-3-540-74686-7

R Core Team. (2017b). R Development Core Team. In *R: A Language and Environment for Statistical Computing* (Vol. 55, pp. 275–286). https://doi.org/http://www.R-project.org
Ramirez-Rubio, O., Daher, C., Fanjul, G., Gascon, M., Mueller, N., Pajín, L., Plasencia, A., Rojas-Rueda, D., Thondoo, M., and Nieuwenhuijsen, M. J. (2019). Urban health: An example of a "health in all policies" A pproach in the context of SDGs implementation. *Globalization and Health*, *15*(1), 1–21. https://doi.org/10.1186/s12992-019-0529-z
Ranaweera, P., Wickremasinghe, R., and Mendis, K. (2020). Preventing the re-establishment of malaria in Sri Lanka amidst the COVID-19 pandemic. *Malaria Journal*, *19*(1), 4–7. https://doi.org/10.1186/s12936-020-03465-5
Rebaudet, S., Sudre, B., Faucher, B., and Piarroux, R. (2013). Cholera in Coastal Africa: A systematic review of its heterogeneous environmental determinants. *Journal of Infectious Diseases*, *208*(SUPPL. 1). https://doi.org/10.1093/infdis/jit202
Reed, F. J., Gaughan, A. E., Stevens, F. R., Yetman, G., Sorichetta, A., and Tatem, A. J. (2018). Gridded population maps informed by different built settlement products. *MDPI*, *3*(3). https://doi.org/10.3390/data3030033
Ribeiro, A. I., Olhero, A., Teixeira, H., Magalhães, A., and Pina, M. F. (2014). Tools for address georeferencing - Limitations and opportunities every public health professional should be aware of. *PLoS ONE*, *9*(12), 1–13. https://doi.org/10.1371/journal.pone.0114130
Richterman, A., Sainvilien, D. R., Eberly, L., and Ivers, L. C. (2018). Individual and household risk factors for symptomatic cholera infection: A systematic review and meta-analysis. *Journal of Infectious Diseases*, *218*(Suppl 3), S154–S164. https://doi.org/10.1093/infdis/jiy444
Rietveld, L. C., Siri, J. G., Chakravarty, I., Arsénio, A. M., Biswas, R., and Chatterjee, A. (2016). Improving health in cities through systems approaches for urban water management. *Environmental Health: A Global Access Science Source*, *15*(Suppl 1). https://doi.org/10.1186/s12940-016-0107-2
Sakijege, T. (2019). Private water distribution as a potential everyday risk: The case of Goba, Dar es Salaam. *Jàmbá Journal of Disaster Risk Studies*, *11*(1), 1–10. https://doi.org/10.4102/jamba.v11i1.775
Saldarriaga, J. G., Ochoa, S., Moreno, M. E., Romero, N., and Cortés, O. J. (2010). Prioritised rehabilitation of water distribution networks using dissipated power concept to reduce non-revenue water. *Urban Water Journal*, *7*(2), 121–140. https://doi.org/10.1080/15730620903447621
Salon, D., and Gulyani, S. (2019). Commuting in Urban Kenya: Unpacking travel demand in large and small Kenyan cities. *Sustainability (Switzerland)*, *11*(14), 1–22. https://doi.org/10.3390/su11143823
Sanchez-Padilla, E., Grais, R. F., Guerin, P. J., Steele, A. D., Burny, M. E., and Luquero, F. J. (2009). Burden of disease and circulating serotypes of rotavirus infection in sub-Saharan Africa: systematic review and meta-analysis. *The Lancet Infectious Diseases*, *9*(9), 567–576. https://doi.org/10.1016/S1473-3099(09)70179-3
Sanchez, G. M., Terando, A., Smith, J. W., García, A. M., Wagner, C. R., and Meentemeyer, R. K. (2020). Forecasting water demand across a rapidly urbanizing region. *Science of The Total Environment*, *730*, 139050. https://doi.org/10.1016/j.scitotenv.2020.139050
Schaetti, C., Sundaram, N., Merten, S., Ali, S. M., Nyambedha, E. O., Lapika, B.,

Chaignat, C. L., Hutubessy, R., and Weiss, M. G. (2013). Comparing sociocultural features of cholera in three endemic African settings. *BMC Medicine*, *11*(1), 1. https://doi.org/10.1186/1741-7015-11-206
Sedgwick, P. (2015). Understanding the ecological fallacy. *BMJ (Online)*, *351*(September), 1–2. https://doi.org/10.1136/bmj.h4773
Sidhwani, P. (2015). Spatial inequalities in big indian cities. *Economic and Political Weekly*, *50*(22), 55–62.
Simiyu, N. L., and Dulo, S. O. (2015). *Spatiotemporal Analysis of Borehole Locations in Nairobi County 1930-2013*. *4*(3), 230–238.
Simiyu, S., Swilling, M., Cairncross, S., and Rheingans, R. (2017). Determinants of quality of shared sanitation facilities in informal settlements: Case study of Kisumu, Kenya. *BMC Public Health*, *17*(1), 1–13. https://doi.org/10.1186/s12889-016-4009-6
Sinyange, N., Brunkard, J. M., Kapata, N., Mazaba, M. L., and Musonda, K. G. (2018). *Cholera Epidemic — Lusaka , Zambia , October 2017 – May 2018* (Vol. 67, Issue 19).
Sousa, A., Scheffler, R. M., Koyi, G., Ngah, S. N., Abu-agla, A., Harrison, M. M., and Nyoni, J. (2014). Health labour market policies in support of universal health coverage: a comprehensive analysis in four African countries. *Human Resources for Health*.
Sow, P. S., Diop, B. M., Maynart-Badiane, M., Sow, A., Ndour, C. T., M, D. N., Ball, D., Badiane, S., and Coll-Seck, A. M. (1999). L'épidémie de choléra de 1995-1996 à Dakar. *Medecine et Maladies Infectieuses*, *29*, 105–109.
Steinmann, P., Keiser, J., Bos, R., Tanner, M., and Utzinger, J. (2006). *2006 - Steinmann - Schisto and water resources development - review of people at-risk*. 411–425. http://infection.thelancet.comvol
Stevens, F. R., Gaughan, A. E., Linard, C., and Tatem, A. J. (2015). Disaggregating census data for population mapping using Random forests with remotely-sensed and ancillary data. *PLoS ONE*, *10*(2), 1–22. https://doi.org/10.1371/journal.pone.0107042
Stoler, J., Fink, G., Weeks, J. R., Otoo, R. A., Ampofo, J. A., and Hill, A. G. (2012a). When urban taps run dry: Sachet water consumption and health effects in low income neighborhoods of Accra, Ghana. *Health and Place*, *18*(2), 250–262. https://doi.org/10.1016/j.healthplace.2011.09.020
Stoler, J., Fink, G., Weeks, J. R., Otoo, R. A., Ampofo, J. A., and Hill, A. G. (2012b). When urban taps run dry: Sachet water consumption and health effects in low income neighborhoods of Accra, Ghana. *Health and Place*, *18*(2), 250–262. https://doi.org/10.1016/j.healthplace.2011.09.020
Syed, S. T., Gerber, B. S., and Sharp, L. K. (2013). Traveling Towards Disease: Transportation Barriers to Health Care Access. *Journal of Community Health*, *38*(5), 976–993. https://doi.org/10.1007/s10900-013-9681-1.Traveling
Tao, Z., Cheng, Y., Zheng, Q., and Li, G. (2018). Measuring spatial accessibility to healthcare services with constraint of administrative boundary: A case study of Yanqing District, Beijing, China. *International Journal for Equity in Health*, *17*(1), 1–12. https://doi.org/10.1186/s12939-018-0720-5
Thomas, M. L. H., Channon, A. A., Bain, R. E. S., Nyamai, M., and Wright, J. A. (2020). Household-reported availability of drinking water in Africa: A systematic review. *Water (Switzerland)*, *12*(9), 1–28. https://doi.org/10.3390/W12092603
Thorn, J., Thornton, T. F., and Helfgott, A. (2015). Autonomous adaptation to global

environmental change in peri-urban settlements: Evidence of a growing culture of innovation and revitalisation in Mathare Valley Slums, Nairobi. *Global Environmental Change*, *31*, 121–131. https://doi.org/10.1016/j.gloenvcha.2014.12.009

Toh, K. Ben, Millar, J., Psychas, P., Abuaku, B., Ahorlu, C., Oppong, S., Koram, K., and Valle, D. (2021). Guiding placement of health facilities using malaria criteria and interactive tool. *Research Square*, 1–17.

Traoré, D., Sy, I., Utzinger, J., Epprecht, M., Kengne, I. M., Baidy, L., Odermatt, P., Faye, O., Cissé, G., and Tanner, M. (2013). Water quality and health in a Sahelian semi-arid urban context: An integrated geographical approach in Nouakchott, Mauritania. *Geospatial Health*, *8*(1), 53–63. https://doi.org/10.4081/gh.2013.54

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K., Colquhoun, H., Kastner, M., Levac, D., Ng, C., Sharpe, J. P., Wilson, K., Kenny, M., Warren, R., Wilson, C., Stelfox, H. T., and Straus, S. E. (2016). A scoping review on the conduct and reporting of scoping reviews. *BMC Medical Research Methodology*, *16*(1), 1–10. https://doi.org/10.1186/s12874-016-0116-4

Troeger, C., Blacker, B. F., Khalil, I. A., Rao, P. C., Cao, S., Zimsen, S. R., Albertson, S. B., Stanaway, J. D., Deshpande, A., Abebe, Z., Alvis-Guzman, N., Amare, A. T., Asgedom, S. W., Anteneh, Z. A., Antonio, C. A. T., Aremu, O., Asfaw, E. T., Atey, T. M., Atique, S., … Reiner, R. C. (2018). Estimates of the global, regional, and national morbidity, mortality, and aetiologies of diarrhoea in 195 countries: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet Infectious Diseases*, *18*(11), 1211–1228. https://doi.org/10.1016/S1473-3099(18)30362-1

Tusting, L. S., Bisanzio, D., Alabaster, G., Cameron, E., Cibulskis, R., Davies, M., Flaxman, S., Gibson, H. S., Knudsen, J., Mbogo, C., Okumu, F. O., von Seidlein, L., Weiss, D. J., Lindsay, S. W., Gething, P. W., and Bhatt, S. (2019). Mapping changes in housing in sub-Saharan Africa from 2000 to 2015. *Nature*, *568*(7752), 391–394. https://doi.org/10.1038/s41586-019-1050-5

Ubosi, N. I. (2018). Prevalence of diarrhoea among infants of child welfare clinics at two teaching hospitals in Lagos, Nigeria. *Journal of Applied Sciences and Environmental Management*, *22*(10), 1707. https://doi.org/10.4314/jasem.v22i10.31

UN-DESA. (2014). World Urbanization Prospects. *United Nations*, *12*, 32. https://doi.org/10.4054/DemRes.2005.12.9

UN-Habitat. (2006). *Nairobi Urban Sector Profile*.

UN-Habitat. (2013). Water and sanitation in the world's cities: Local action for global goals. *Water and Sanitation in the World's Cities: Local Action for Global Goals*, 1–278. https://doi.org/10.4324/9781849774284

UN-HABITAT. (2016). Urbanization and development: Emerging Futures. *United Nations Human Settlements Programme (UN-Habitat)*.

UN-HABITAT. (2018). *Adequate Housing and Slum Adequate Housing and Slum*.

UNEP. (2019). Emerging Issues of Environmental Concern. In *United Nations Environment Programme*.

UNESCO, and UN-Water. (2020). WATER AND CLIMATE CHANGE. In *Water and Climate Change*. https://doi.org/10.5040/9780755606511.0014

UNICEF, and WHO. (2017). *JMP Ladder chart*. https://washdata.org/data/household#!/dashboard/new

UNICEF, and WHO. (2019). *Progress on household drinking water, sanitation and* *hygiene 2000-2017. Special focus on inequalities.* https://washdata.org/sites/default/files/documents/reports/2019-07/jmp-2019-wash-households.pdf

United Nations. (2015a). *Sustainable Develoment Goals: 17 Goals to transform our world*.

United Nations. (2015b). *Sustainable Development Goals: 17 Goals to Transform our world*. United Nations. http://www.un.org/sustainabledevelopment/water-and-sanitation/

United Nations. (2018). The World 's Cities in 2018. *United Nations*, 34.

United Nations. (2020). The Sustainable Development Goals Report 2020. *United Nations Publication Issued by the Department of Economic and Social Affairs*, 1–64.

United Nations Department of Economic and Social Affairs. (2018). World Urbanization Prospects. In *Demographic Research*. file:///C:/Users/rocey/Downloads/WUP2018-Report.pdf

United Nations Economic Commission for Africa. (2017). *Unlocking the Potential of open government in Africa*. *9431*, 2016–2020.

United Nations, and Water Supply and Sanitation Collaborative Council. (2011). *The Human Right to Water and Sanitation Media brief. April 2011*, 1–8. http://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf

Usman, A., Sarkinfada, F., Mufunda, J., Nyarang'o, P., Mansur, K., and Daiyabu, T. M. (2005). Recurrent cholera epidemics in Kano - Northern Nigeria. *Central African Journal of Medicine*, *51*(3–4), 34–38.

Vairavamoorthy, K., Gorantiwar, S. D., and Pathirana, A. (2008). Managing urban water supplies in developing countries - Climate change and water scarcity scenarios. *Physics and Chemistry of the Earth*, *33*(5), 330–339. https://doi.org/10.1016/j.pce.2008.02.008

van den Berg, C. (2015). Drivers of non-revenue water: A cross-national analysis. *Utilities Policy*, *36*, 71–78. https://doi.org/10.1016/j.jup.2015.07.005

van den Berg, C., and Danilenko, A. (2017). Performance of Water Utilities in Africa. *World Bank*. https://doi.org/10.1596/26186

van Zwanenberg, P. (1975). Kenya's Primitive Colonial Capitalism : The Economic Weakness of Kenya's Settlers up to 1940. *Canadian Journal of African Studies*, *9*(2), 277–292.

Vivien, F., and Briceno-Garmendia, C. (2010). *Africa's Infrastructure : A Time for Transformation*. World Bank. https://openknowledge.worldbank.org/handle/10986/2692 License: CC BY 3.0 IGO

Von Nguyen, D., Sreenivasan, N., Lam, E., Ayers, T., Kargbo, D., Dafae, F., Jambai, A., Alemu, W., Kamara, A., Islam, M. S., Stroika, S., Bopp, C., Quick, R., Mintz, E. D., and Brunkard, J. M. (2014). Cholera epidemic associated with consumption of unsafe drinking water and street-vended water-Eastern Freetown, Sierra Leone, 2012. *American Journal of Tropical Medicine and Hygiene*, *90*(3), 518–523. https://doi.org/10.4269/ajtmh.13-0567

Wangia, E., and Kandie, C. (2018). *Policy Brief:Refocusing on quality of care*. http://www.health.go.ke/wp-content/uploads/2019/01/UHC-QI-Policy-Brief.pdf

WASREB. (2019). *Guideline on Water Vending*. 1–42.

Water Resources Authority. (2018). *Water Resources Situation Report* (Issue August). https://wra.go.ke/wp-content/uploads/2019/07/National-Water-Situation-

Report_2017-18.pdf
Watson, V. (2014). African urban fantasies: Dreams or nightmares? *Environment and Urbanization*, *26*(1), 215–231. https://doi.org/10.1177/0956247813513705
WHO. (1993). Guidelines for drinking-water quality. *Water Supply*, *11*(3–4), 1–16.
WHO. (2016). *Health as the Pulse of the New Urban Agenda*. *October*, 56.
WHO. (2018). Weekly epidemiological record: Cholera. *Weekly Epidemiological Record*, *16*(93), 201–220. http://www.who.int/wer
WHO. (2020a). Domestic Water Quantity , Service Level and Health, second edition. In *World Health Organization*. http://www.who.int/water_sanitation_health/diseases/wsh0302/en/
WHO. (2020b). *Water*. https://www.afro.who.int/health-topics/water
WHO, and CDC. (2010). *Integrated Disease Surveillance and Response in the African Region*. 373.
Winter, S. C., Obara, L. M., and Barchi, F. (2019). Environmental correlates of health-related quality of life among women living in informal settlements in Kenya. *International Journal of Environmental Research and Public Health*, *16*(20). https://doi.org/10.3390/ijerph16203948
Winter, S., Dreibelbis, R., and Barchi, F. (2019). Women's sanitation practices in informal settlements: A multi-level analysis of factors influencing utilisation in Nairobi, Kenya. *Global Public Health*, *14*(5), 663–674. https://doi.org/10.1080/17441692.2018.1534256
Winter, S., Dzombo, M. N., and Barchi, F. (2019). Exploring the complex relationship between women's sanitation practices and household diarrhea in the slums of Nairobi: a cross-sectional study. *BMC Infectious Diseases*, *19*(1), 242. https://doi.org/10.1186/s12879-019-3875-9
Woltjer, J. (2014). A Global Review on Peri-Urban Development and planning. *Journal of Regional and City Planning*, *25*(1), 10–11. http://www.tulane.edu/~sbc2003/pdfdocs/0561.PDF
World Bank. (2018). *Population living in slums (% of urban population)*. https://data.worldbank.org/indicator/EN.POP.SLUM.UR.ZS?locations=KE
World Bank. (2019). *Population growth (% annual)*. https://data.worldbank.org/indicator/SP.POP.GROW?end=2016&locations=KE&start=1960&view=chart
World Bank. (2020). *World Development Indicators*. https://data.worldbank.org/indicator/ER.H2O.INTR.PC?end=2014&locations=KE&start=1962&view=chart
World Bank Group. (2014). *Kenya state of the cities:Baseline Survey*. 68–70.
World Bank, and Infrastructure Consortium for Africa. (2010). *Africa's Infrastructure: A Time for Transformation*. 1–28.
World Gastroenterology Organisation. (2012). Acute diarrhea in adults and children: A global perspective. World Gastroenterology Organisation Global Guidelines. *J Clin Gastroenterol*, *47*(1), 12–20.
World Health Organization. (2006). Working together for Health. *Actual Problems of Economics*, *9*, 3–10.
World Health Organization. (2015). *Human resources for health information system: Minimum Data Set for Health Workforce Registry*. http://www.who.int/hrh/statistics/minimun_data_set.pdf
WorldPop. (2019). *WorldPop gridded population estimate datasets and tools*.
WorldPop. (2020). *Open Spatial Demographic Data and Research*.
Wright, J., Gundry, S., and Conroy, R. (2004). Household drinking water in

developing countries: A systematic review of microbiological contamination between source and point-of-use. *Tropical Medicine and International Health*, *9*(1), 106–117. https://doi.org/10.1046/j.1365-3156.2003.01160.x
Xiao-jun, W., Jian-yun, Z., Shahid, S., Xing-hui, X., Rui-min, H., and Man-ting, S. (2014). Catastrophe theory to assess water security and adaptation strategy in the context of environmental change. *Mitigation and Adaptation Strategies for Global Change*, *19*(4), 463–477. https://doi.org/10.1007/s11027-012-9443-x
Yahdjian, L., Sala, O. E., and Havstad, K. M. (2015). Rangeland ecosystem services: Shifting focus from supply to reconciling supply and demand. *Frontiers in Ecology and the Environment*, *13*(1), 44–51. https://doi.org/10.1890/140156
Yang, H., Bain, R., Bartram, J., Gundry, S., Pedley, S., and Wright, J. (2013). Water safety and inequality in access to drinking-water between rich and poor households. *Environmental Science and Technology*, *47*(3), 1222–1230. https://doi.org/10.1021/es303345p
Yilgwan, C. ., Yilgwan, G., and Ii, A. (2010). Domestic Water Sourcing and the Risk of Diarrhea : A Cross-Sectional Survey of a. *Jos Journal of Medicine*, *5*(1), 34–37.
Yongsi, H. B. N. (2010). Suffering for water, suffering from water: Access to drinking-water and associated health risks in Cameroon. *Journal of Health, Population and Nutrition*, *28*(5), 424–435. https://doi.org/10.3329/jhpn.v28i5.6150
Zhang, X. Q. (2016). The trends, promises and challenges of urbanisation in the world. *Habitat International*, *54*(13), 241–252. https://doi.org/10.1016/j.habitatint.2015.11.018
Zhang, Z., Wang, Y., Chen, P., He, Z., and Yu, G. (2017). Probe data-driven travel time forecasting for urban expressways by matching similar spatiotemporal traffic patterns. *Transportation Research Part C: Emerging Technologies*, *85*(August), 476–493. https://doi.org/10.1016/j.trc.2017.10.010
Zuur, A. F., Ieno, E. N., and Elphick, C. S. (2010). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution*, *1*(1), 3–14. https://doi.org/10.1111/j.2041-210x.2009.00001.x

Chapter Nine: Annexes

Annex 1: List of studies included in the scoping review

No	author(s)	Study period	Study design	Target population	Study population sample size	Rationale given for sample size	Sample type and size	Water insufficiency metric	Coping mechanism employed	Disease/Syndrome studied (method of measuring)[1]	Type of water tested	Water quality tests	Outbreak investigation	Analysis methods	Confounders/ effect modifiers/ other transmission pathways included in analysis
1	Degbey et al(2011)	2008-2009	Cross-sectional ecological	Patients visiting health facilities	110	No	Water-110	NR	Digging wells, collecting water from alternative sources	Cholera (C), typhoid (C), amoebiasis (C), dysentery(C), diarrhoea (C), gastroenteritis (C)	Water points	Faecal indicator organism test, pathogens test	No	Bivariate (Pearson chi-square tests; Fischer exact tests)	
2	Navab-Daneshmand et al (2018)	2016	Cross-sectional individual	Households	142	Yes	Soil from outdoor location closest to the house entrance- 142; Water-244 Hand rinse samples - 142	Proportion with running tap water	Water storage in household	Diarrhoea (SR)	Stored water in household	Organoleptic water quality; Faecal indicator organism test	No	Multivariate (multiple regression models), bivariate (Pearson correlation coefficients)	Faecal indicator organism test result for soil, handwashing water, hands before washing, diarrhea incidence, number of assets owned, sanitation (presence of animals, toilet structure, toilet cleanliness, toilet location), household hygiene (presence of

															trash, presence of flies), Location of handwashing facility, presence of soap and water in handwashing facility, Organoleptic quality of stored water, type of opening of water storage container
3	Traore et al (2013)	2008-2009	Cross-sectional ecological	municipalities	13,705	No	Water-150	Proportion with access to piped water, L/P/D	Purchasing water, Collecting water from alternative sources	Diarrhoea (C)	Water points	Faecal indicator organism test	No	Bivariate (Correlation coefficient)	Quality of water, incidence of waterborne disease/syndrome
4	Sinyange et al (2018)	2017-2018	Cross-sectional individual - KAP, Case-control	Households	267,205	No	Water-220, stool-4	NR	NR	Cholera (SR)	Water points	Faecal indicator organism test, free chlorine residual	Yes	Multivariate (NR)	Contact with a person with cholera, consumption of untreated water, gender
5	Ako et al (2009)	1995-2006	Cross-sectional ecological	Households	300	No	Water-10	Proportion with access to piped water	Collecting water from alternative sources	Typhoid (C), diarrhoea (C), amoebic dysentery (C), gastroenteritis (C)	Water points	Faecal indicator organism test, organoleptic water quality, free chlorine residual	No	NR	
6	Winter et al (2019)	2016	Cross-sectional individual	women	550	No	N/A	Proportion with access to piped water	Purchasing water, Collecting water from	Diarrhoea (SR)	N/A	N/A	No	Bivariate (Pearson chi-square tests),	Age, level of education, employed, has children, level of household

									alternative sources					multivariate (logistic regression)	income, type of toilet used during the day and at night, source of water, toilet hygiene and accessibility, WASH knowledge and practices
7	Sakijege (2019)	2018	Cross-sectional individual	households	32	No	Water-3	NR	Drilling boreholes, collecting water from alternative sources, purchasing water, storage tanks	Typhoid (SR), diarrhoea (SR), dysentery (SR)	Water points	organoleptic water quality, Faecal indicator organism test	No	NR	
8	Muti et al (2014)	2011	Case-control individual	respondents	230	No	Water-25 Stool-NR	NR	Water storage in households, water treatment, collecting water from alternative sources	Typhoid (CC), diarrhoea (SR)	Water points	Free chlorine residual, faecal indicator organism test	Yes	Multivariate (NR)	Burst sewer pipe within 500 metres from home, typhoid contact at home, water from an alternative source, type of storage water container, boil drinking water
9	Oguntoke et al (2009)	1999-2004	Cross-sectional ecological, cross-sectional individual	Patients visiting health facilities, households	350	No	Water-NR	Availability of piped water	Collecting water from alternative sources, purchasing water, water	Cholera (C), typhoid (C), dysentery (C), gastroenteritis (C)	Stored water in household	faecal indicator organism test, pathogen test	No	Bivariate (correlation coefficient) Multivariate (simple linear	Water treatment, level of income, household size

									treatment, rainwater harvesting					regression model)	
10	Dos Santos et al, (2015)	2012	Cross-sectional individual	children under 10 years	702	No	N/A	L/P/D, Proportion with access to piped water, time spent to collect water	Purchasing water, water storage in household, rainwater harvesting	Diarrhoea (SR)	N/A	N/A	No	Multivariate (logistic regression model)	Main source of drinking water, time spent in water collection, per capita water available, type of water storage container, use of rainwater, handwashing before eating, sex of household head, level of education of household head, livelihood of household head, economic status of household head, number of children in the household, type of sanitation
11	Essayagh et al (2019)	2013-2016	Cohort	Typhoid confirmed cases	322	Yes	N/A	Proportion with access to piped water	Collecting water from alternative sources	Typhoid (C)	N/A	N/A	Yes	Bivariate (Wald Test)	
12	Barzilay et al (2011)	2005	Cohort	HIV positive women	242 baseline and 187 follow-up visits	Yes	Water (baseline-242, follow-up	Proportion with an improved water supply	water storage at households, water treatment	Diarrhoea (SR)	Stored water in household	organoleptic water quality,	No	Bivariate (Wilcoxon's Signed Ranked	

							visits-187)		purchasing water					test; Wilcoxon's Ranked Sums test)	
13	Baker et al (2013)	2007-2010	Case-control	children <5 years	4,096	Yes	Water-63	Time taken in fetching water, proportion with access to piped water	Purchasing water, Collecting water from alternative sources, water storage in households	Diarrhoea (C)	Water points and stored water in household	faecal indicator organism test, free residual chlorine	No	Bivariate (Pearson chi-square tests, Fischer exact test, T-tests), Multivariate (logistic regression model)	Collecting water, continuous access to water, time taken to collect water, breastfeeding, both parents living at home, wealth quintile index, caretaker's level of education
14	Kone-Coulibaly et al (2010)	2008	Case-control	households	280	Yes	N/A	Unpredictable interruptions, proportion with access to piped water	Collecting water from alternative sources	Cholera (C), diarrhoea (SR)	N/A	N/A	Yes	Multivariate (logistic regression models)	Contact with a diarrheal patient, experiencing unpredictable water interruptions, level of education, source of drinking water, attending a gathering, consuming hot food, consuming cold food, having received health education on cholera
15	Yilgwan et al (2010)	2005	Cross-sectional individual	households	200	No	N/A	Proportion with access to piped water	Water treatment, collectin	Diarrhoea (SR)	N/A	N/A	No	Multivariate (logistic	Family size, Number of children in the household,

									g water from alternative sources					regression model)	educational status of household head, income level of household head, Domestic source of water, water treatment
16	Schaetti et al (2013)	2008	Cross-sectional individual	respondents	356	No	N/A	NR	NR	Cholera (SR)	N/A	N/A	Yes	Bivariate (Wilcoxon test, Kruskal-Wallis test, Pearson chi-square test, Fischer exact test)	
17	Dunne et al (2001)	1999	Case-control	Cases-households of women who attended HIV clinic	120	No	Water-120	Proportion with access to piped water, unpredictable interruptions	water storage in household, purchasing water, water treatment	Diarrhoea (SR)	Stored water in household	faecal indicator organism test, free residual chlorine	No	NR	
18	Machdar et al (2013)	2010	Cross-sectional individual	Households	110	No	Water-NR	Proportion with access to piped water, unpredictable interruptions	water storage in household, purchasing water, collecting water from alternative sources	rotavirus (SR), cryptosporidium (SR), diarrhoea (SR)	Stored water in household	faecal indicator organism test, pathogen tests	No	Cost effective analysis	
19	Usman et al (2005)	1995-2001	Cross-sectional ecological	Patients visiting health facilities	6,165	No	Water-NR	NR	Collecting water from	Cholera (C)	Water points	faecal indicator organism test,	Yes		

									alternative sources						
20	Endris et al (2019)	2016	Case-control	households	300	Yes	Stool-NR	NR	Collecting water from alternative sources, purchasing water	Cholera (CC)	N/A	N/A	Yes	Bivariate (Pearson chi-square test)	Source of water consumed, water treatment, level of hygiene/sanitation, type of food consumed, attended a gathering
21	Ubosi (2018)	2018	Cross-sectional individual	Mothers of infants <6 months	202	No	N/A	Proportion with access to piped water	Collecting water from alternative sources, purchasing water	Diarrhoea (SR)	N/A	N/A	No	Bivariate (Pearson correlation coefficients, Chi-square test)	Exclusive breastfeeding, piped water supply
22	Blanton et al (2015)	2010	Cross-sectional individual	households	39	No	Water-398	Proportion with access to piped water, scheduled water interruptions	Water storage in household, purchasing water, water treatment	Cholera (SR)	Water points and stored water in household	faecal indicator organism test, free chlorine residual	Yes	Bivariate (T-tests, Pearson chi-square tests, Wilcoxon rank-sum tests)	
23	Kuitchaet al (2008)	2007	Cross-sectional individual	households	1,397	No	N/A	Proportion with access to piped water	Collecting water from alternative sources, water treatment, purchasing water	Dysentery (SR), diarrhoea (SR), typhoid (SR)	N/A	N/A	No	Bivariate (Kruskal Wallis H-test)	
24	Yongsi (2010)	Survey: 2002; Microb	Cross-sectional individual	children between 6-59 months	3,034	No	Water-508	Proportion with access	Collecting water from	Diarrhoea (SR)	Water points and	faecal indicator organism	No	Bivariate (Chi-square	

		iological & Medical Investigation: 2005 & 2008						to piped water	alternative sources		Stored water in household	test, pathogen tests		test,), spatial analysis
25	Abaje et al (2009)	2008	Cross-sectional individual	households	220	No	N/A	Proportion with access to piped water, scheduled interruptions, distance to the water source, L/P/D	Collecting water from alternative sources, purchasing water, water treatment	Cholera (SR), Typhoid (SR), Dysentery (SR)	N/A	N/A	N/A	Bivariate (Chi-square tests)
26	Nkhuwa (2003)	Chemical and bacteriological analysis from water utility company: 1995-1997, 1999-2000; Health facility data: 1997 & 1999	Cross-sectional ecological	Patients visiting health facilities	1,864 in 1997, 6,219 in 1999	No	Water-14	Proportion with access to piped water	Collecting water from alternative sources, drilling boreholes	Cholera (C)	Water points	faecal indicator organism test, free chlorine residual, organoleptic water quality,	No	NR
27	Sow et al (1999)	1995-1996	Cross-sectional ecological	Cholera cases in health facilities	141 in 1995, 182 in 1996	No	N/A	Proportion with access to piped water	Purchasing water, collecting water from	Cholera (C)	N/A	N/A	Yes	NR

									alternative sources						
28	Julvez et al (1998)	1995 (human samples), 1996 (water samples)	Cross-sectional individual	Households, children <10 years	322 people, 161 children	No	Water-15	L/P/D	Collecting water from alternative sources	Amoebiasis (SR)	Water points	faecal indicator organism test, pathogen test	No	NR	
29	Adane et al (2017)	2014	Case-control	Children <5 years	760	Yes	Water-192	scheduled interruptions, L/P/D,	water storage in households	Diarrhoea (SR)	Stored water in household	faecal indicator organism test	No	Multivariate (Multiple logistic regression models)	
30	Akinbo et al (2010)	2008-2009	Case-control	HIV-infected persons	500	No	Stool-500	Proportion with access to piped water	Collecting water from alternative sources	Cryptosporidium (CC), diarrhoea (SR)	N/A	N/A	No	Bivariate (Pearson chi-square test)	
31	Nguyenet al (2014)	2012	Case-control	Individuals >= 5 years	147	No	Water-80, Stool-30	Proportion with access to an improved source of water, scheduled interruptions	Water storage in households, purchasing water, illegal connections	Cholera (C)	Stored water in household	organoleptic water quality	Yes	Multivariate (Multiple logistic regression models), Bivariate (Wald Test)	Vended water, unsafe water, education level of household head, consuming hot food, consuming crab, consuming okra
32	Stoler et al (2011)	2009-2010	Cross-sectional individual	Women, children	2093 women, 810 children	Yes	N/A	Scheduled water interruptions, proportion with access to piped water	Purchasing water, water storage in households	Diarrhoea (SR)	N/A	N/A	No	Multivariate (multiple logistic regression models, random mixed effects models), Bivariate (ANOVA, chi-	Mother's self-reported overall health, purchased water as primary source of drinking water, daily bathroom expense, days of water rationing

square
test)

[1]CC- Culture confirmed, C- Clinically confirmed, SR- self-reported
NR-Not Reported; N/A- Not Available

Annex 2: Research License

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Annex 3: Publications- The nexus between improved water supply and water-borne diseases in urban areas in Africa: a scoping review protocol

Nyamai Mutono[1,2], James Wright[3], Henry Mutembei[1,4], Josphat Muema[2,5], Mair Thomas[3], Mumbua Mutunga[5], Samuel Mwangi Thumbi[1,5-8]

[1]Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Nairobi, Kenya
[2]Washington State University Global Health – Kenya, Nairobi, Kenya
[3]Geography and Environmental Science, University of Southampton, Southampton, UK [4]Department of Clinical Studies, Faculty of Veterinary Medicine, University of Nairobi, Nairobi, Kenya [5]Institute of Tropical and Infectious Diseases, University of Nairobi, Nairobi, Kenya
[6]Paul G Allen School for Global Animal Health, Washington State University, Pullman, USA
[7]Institute of Immunology and Infection Research, University of Edinburgh, Edinburgh, UK
[8]NIHR Global Health Research Unit Tackling Infections to Benefit Africa (TIBA), University of Edinburgh, Edinburgh, UK

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Latest published: 08 Dec 2020, **3**:12
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Abstract

Introduction: Currently, an estimated two thirds of the world population is water insufficient. As of 2015, one out of every five people in developing countries do not have access to clean sufficient drinking water. In an attempt to share the limited resource, water has been distributed at irregular intervals in cities in developing countries. Residents in these cities seek alternative water sources to supplement the inadequate water supplied. Some of these alternative sources of water are unsafe for human consumption, leading to an increased risk in water-borne diseases. Africa contributes to 53% of the diarrheal cases reported globally, with contaminated drinking water being the main source of transmission. Water-borne diseases like diarrhea, cholera, typhoid, amoebiasis, dysentery, gastroenteritis, cryptosporidium, cyclosporiasis, giardiasis, guinea worm and rotavirus are a major public health concern. The main objective of this scoping review is to map the available evidence to understand the sources of water among residents in cities in Africa and the relationship between clean water sufficiency and water-borne diseases in urban Africa.

Methods and analysis: The search strategy will identify studies published in scientific journals and reports that are directly relevant to African cities that have a population of more than half a million residents as of 2014 AND studies on the ten emerging water-borne diseases, which are diarrhea, cholera, typhoid, amoebiasis, dysentery, gastroenteritis, cryptosporidium, cyclosporiasis, giardiasis, guinea worm and rotavirus.

Ethics and dissemination: This scoping review did not require any formal ethical approval. The findings will be published in a peer- reviewed journal.

Keywords
Water-borne diseases, water insufficiency, scoping review, African cities, water supply

Open Peer Review

Reviewer Status ✔ ✔

	Invited Reviewers	
	1	**2**
version 2 (revision) 08 Dec 2020	✔ report	✔ report
version 1 05 May 2020	? report	? report

1. **Batsirai Majuru**, World Health Organization, Geneva, Switzerland
2. **David Musoke**, Makerere University College of Health Sciences, Kampala, Uganda

Any reports and responses or comments on the article can be found at the end of the article.

Corresponding author: Nyamai Mutono (mutono.nyamai@wsu.edu)

Author roles: Mutono N: Conceptualization, Data Curation, Formal Analysis, Investigation, Writing – Original Draft Preparation, Writing – Review & Editing; **Wright J**: Methodology, Supervision, Visualization, Writing – Review & Editing; **Mutembei H**: Methodology, Supervision, Writing – Review & Editing; **Muema J**: Data Curation, Investigation, Methodology, Validation; **Thomas M**: Data Curation, Investigation, Validation; **Mutunga M**: Data Curation, Investigation, Methodology, Validation; **Thumbi SM**: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

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First published: 05 May 2020, **3**:12 https://doi.org/10.12688/aasopenres.13063.1

REVISED Amendments from Version 1

The current version includes a more detailed definitions section which standardises the key terms used in this protocol. In addition, the title, abstract and the inclusion and exclusion criteria have been amended to ensure the aim and the scope of the study is clear and precise. Details on the variables to be extracted from the articles for full-text screening have been clearly stated to capture indicators on water sources, sufficiency and safety with occurrence of waterborne diseases in cities in Africa. Finally, the presentation of results has been improved to ensure the study locations of the studies reviewed will be linked to the coordinates from peer reviewed and publicly available water scarcity map from the Water Footprint Network to allow us to make observations on the trend between cities with prevalence of waterborne diseases and water scarcity. The resultant maps will enable researchers to identify areas that have gaps in knowledge and research needs.

Any further responses from the reviewers can be found at the end of the article

Introduction

Urbanization in sub-Saharan Africa (SSA) is growing at 4% annually, with the population living in urban areas projected to double by 2050[1]. This rapid urbanisation outpaces the development of infrastructure in these cities leading to inad- equate access to basic amenities, including good housing, adequate social amenities, and continuous supply of safe drinking water to city residents[2]. Poor access to clean water driven by rapid population growth, increased water demand, infrastructural constraints, and consumer response to cope with insufficient supply of safe water through use of alternative water sources is associated with ill-health[3]. This rapid urbani- sation is anticipated to accelerate demand for water[2,4], which lies at the nexus of food security, poverty reduction, economic growth, energy production and human health[5,6].

Currently, an estimated 40% of the global population is water insufficient[7]. The World Health Organisation (WHO) international benchmark states a minimum water requirement per person per day of between 50 and 100 litres in order to meet basic domestic needs[8]. However, by 2017, only half of the population residing in urban SSA had access to safely managed drinking water that was free from contamination. Goal 6 of the Sustainable Development Goals (SDGs) aims to attain sustain- able management and availability of sufficient clean water and sanitation for all[7]. This aligns with Aspiration 1 of the African Union Agenda 2063 objectives, on sustainable development in Africa[9].

Residents of urban areas in Africa depend on both improved and unimproved water sources including piped water, boreholes, wells, vendors and surface water[8]. However, the Africa Infrastructure Country Diagnostic report by the World Bank categorised piped water as the only major source of improved water in SSA[10]. In 2017, piped water was only accessible to 230 million people (61%) in urban areas in this region[11]. In an attempt to share and ration limited resources, piped water has been distributed in cities in developing countries at irregular intervals, known as intermittent water supplies (IWS)[12]. Residents have responded to these challenges by seeking alternative sources of water, some of which are unsafe for human consumption[13,14]. Half (53%) of the water sources in Africa are faecally contaminated, predisposing the people to the risk of diarrheal diseases[15].

In 2016, more than half a billion deaths in SSA were attributed to diarrheal diseases with contamination of drinking water iden- tified as one of the leading risk factors[16]. Major pathogens, such as *Escherichia coli*, cryptosporidium, *aeromonas* spp, shigella and entamoeba, often found in unsafe water, are associ- ated with moderate-to-severe diarrhea which is especially life threatening to infants[17]. Disease surveillance and response in SSA lists cholera, diarrheal diseases and typhoid fever as some of the priority diseases associated with poor quality water, that should be regularly monitored and reported[18].

Previous reviews have explored the prevalence of intermit- tent water supplies in low income settings[19], household water availability across Africa[20], the global burden of diarrheal diseases[16,21] and implications of intermittent water supply on gastrointestinal illness[22]. We have found no review focused on urban areas in Africa and the implications of water-borne diseases as a result of intermittent piped water in this region.

This manuscript details the protocol to a review of the link between insufficient piped water supply and waterborne diseases and syndromes in urban Africa. In doing so, it seeks to address the following research question: "what is the proportion of resi- dents with safely managed water in cities in Africa and what is the correlation with water-borne diseases and the symptoms?" This will be achieved by synthesising findings of studies on:
a) water sufficiency in cities within Africa; b) consequences of rapid urbanisation on water sufficiency in African cities; and
c) the linkages between water sufficiency and water-borne diseases and their symptoms in Africa.

This work should provide information to guide policies that aim to help Africa achieve one of its Agenda 2063 aspirations on provision of adequate basic necessities for urban populations in the region[9].

Definitions

For the purpose of this protocol and the planned review, key terms are defined and classified as follows:

- **Waterborne disease:** includes cholera, typhoid, amoebiasis, cyclosporiasis and giardiasis diseases[16–18]
- **Symptoms of waterborne diseases:** focus on diarrhea, dysentery and gastroenteritis[16,17]
- **Etiological agents of diarrheal diseases:** include cryptosporidium and rotavirus[16,17]
- **Water insufficiency:** is classified as having less than 50 litres per person per day[8]

- **City:** an urban area with a population of more than half a million residents[23]

Methods

The scoping review will use the Joanna Briggs Institute methodology guidance[24] and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for conducting systematic reviews and meta-analysis (http://www.prisma-statement.org). These methodologies have been used for published scoping reviews[25,26].

Inclusion criteria

The review will include the following criteria:

1) Studies undertaken in African Union member states.

2) Studies describing the water situation in cities, classified as urban areas with greater than half a million residents. Since the classification of a city and urban environments is not standardised[2], we use areas with a population greater than 0.5 million people to be consistent with the UN report that estimates one in every three people will reside in cities with at least half a million inhabitants by 2030[23] (Figure 1). The list of the cities that meet this criterion have been selected from the United Nations World Urbanisation Prospects of 2014[27].

3) Studies focusing on water-borne diseases, symptoms and etiological agents:

a) Diseases include cholera, typhoid, amoebiasis, cyclosporiasis and giardiasis diseases

b) Symptoms include diarrhea, dysentery and gastroenteritis

c) Etiological agents include cryptosporidium and rotavirus

4) Studies published in scientific journals or grey literature from government or non-governmental organisations

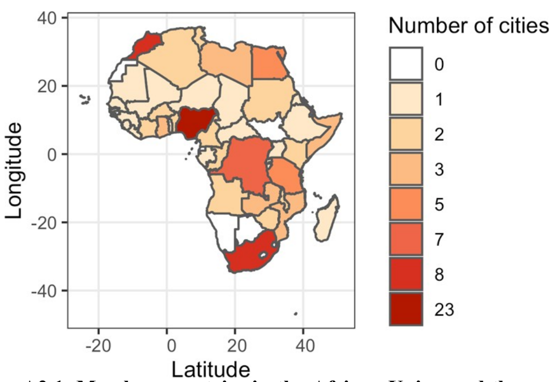

Figure A2.1. Member countries in the African Union and the number of cities with a population greater than half a million residents. Source of data: United Nations World Urbanisation Prospects, 2014[27].

Exclusion criteria

1) Studies not written in the English or French language

2) Systematic reviews

3) Studies conducted in non-member states of the African Union

Search strategy

Comprehensive literature searches will be undertaken in Embase, MEDLINE, Web of Science and Google Scholar databases. These four databases have been identified as the optimal combination of databases that will guarantee adequate coverage of studies for this scoping review[28].

The search strategy will take a three-step process. The first step will involve carrying out a limited search in MEDLINE, Google Scholar (first 500 results), Embase and Web of Science databases. The text and index terms that are used to describe the articles will be assessed. The second step will include searches using the keywords and index terms. In the final step, we will go through the references to identify key articles that might have been missed in the first two steps. The search terms used in the study are seen in Table 1.

Study selection

Once the searches have been undertaken in the databases, the title and abstracts will be extracted from the articles. Duplicates will be removed, and the review team will screen the studies using two levels: initial screening and full-text screening. During the initial screening process, three reviewers will read the abstracts of the studies captured by the search terms and assess their relevance in light of the inclusion criteria. To ensure consistency, 10% of all the studies will be randomly selected and independently reviewed by one other reviewer. Any inconsistencies between the primary and secondary reviewers will be discussed and a consensus reached.

Full text articles will be obtained for the studies that pass the initial screening stage. Microsoft Excel (version 16.36) will be used to store the extracted data. Table 2 shows the characteristics that will be extracted from each study. Of the data extracted, 10% will be randomly selected and independ- ently reviewed by one other reviewer. Any inconsistencies amongst the reviewers will be discussed and an agreement will be reached.

All irrelevant studies will be removed and the reason for their exclusion will be recorded. In this stage, another 10% of the studies will be sampled and shared with the secondary reviewer who will exclude or include the studies based on their rele- vance to the study objective. Consensus will be reached for any discrepancies in the studies among the reviewers.

Presentation of results

If a sufficient number of studies report on the effect of water insufficiency on health outcomes, we will calculate heterogeneity

Table 1. Search terms that will be used to identify studies.

Parameter	Search terms
Population	Huambo OR Luanda OR Cotonou OR "Abomey-Calavi" OR "Abomey Calavi" OR Ouagadougou OR Bobo-Dioulasso OR "Bobo Dioulasso" OR Bunjumbura OR Younde OR Yaounde OR Douala OR Bangui OR Ndjamena OR Brazaville OR Pointe-Noire OR "PointeNoire" OR Abidjan OR Bouake OR Kinsasha OR Cairo OR "Al Qahirah" OR Al-Qahirah OR Alexandria OR "Al-Iskandariyah" OR "Al Iskandariyah" OR "Port Said" OR "Bur Said" OR "Addis Ababa" OR Libreville OR Banjul OR Accra OR Kumasi OR Conakry OR Nairobi OR Mombasa OR Monrovia OR Antananarivo OR Lilongwe OR "Blantyre-Limbe" OR "Blantyre Limbe" OR Bamako OR Nouakchott OR Casablanca OR "Dar-el-Beida" OR "Dar el Beida" OR Rabat OR Nampula OR Tetouan OR Fes OR Marrakech OR Tangier OR Tanger OR Maknes OR Meknes OR Agadir OR Maputo OR Matola OR Niamey OR Lagos OR Kaduna OR Akure OR Kano OR Abuja OR Aba OR Kigali OR Dakar OR Freetown OR CapeTown OR Durban OR Pretoria OR "Port Elizabeth" OR Bloemfontein OR "Dar es Salaam" OR Arusha OR Mbeya OR Lome OR Kampala OR Kitwe OR Lusaka OR Harare OR Bulawayo OR "Benin City" OR Enugu OR Ibadan OR Ikorodu OR Ilorin OR Jos OR Maiduguri OR Nnewi OR Onitsha OR Oshogbo OR Owerri OR "Port Harcourt" OR Sokoto OR Umuahia OR Oyo OR Warri OR Zaria OR Hargeysa OR Merca OR Mogadishu OR Muqdisho OR Johannesburg OR Soshanguve OR Vereeniging OR Khartoum OR "Al-Khartum" OR "Al Khartum" OR Nyala OR Safaqis OR Tunis OR Mwanza OR Zanzibar OR Ndola OR Algiers OR "El Djazair" OR Wahran OR Oran OR Bukavu OR Kananga OR Kisangani OR Lubumbashi OR "Mbuji-Mayi" OR "Mbuji Mayi" OR Tshikapa OR Djibouti OR "Al-Mansurah" OR "Al Mansurah" OR "As-Suways" OR "As Suways" OR Asmara OR "Sekondi Takoradi" OR Banghazi OR Misratah OR Tarabulus OR Tripoli
	AND
Exposure	water AND (scarc* OR intermittent OR break* OR ratio* OR deficit OR deficien* OR unavailab* OR continu* OR interrupt* OR stress OR supply OR sufficien* OR insufficien*)
	AND
Outcome	"water borne" OR "water-borne" OR cholera OR typhoid OR diarrhea* OR diarrhoea OR amoebiasis OR dysentery OR gastroenteritis OR cryptosporidi* OR cyclosporiasis OR giardiasis OR rotavirus

Table 2. Variables to be extracted from the articles for full-text screening.

	Variable	Details
1	Authors	Authors of the article
2	Publication type	Thesis, article
3	Title of the article	Full title
4	Year of publication	Year the article was published or written
5	Geographical scope of the study	City/cities the study was conducted
6	Study type	
7	Duration of the study (if applicable)	
8	Rate of urbanisation	Metric, population of the city
9	Water demand/supply	Main water source, main water distributor, water demand
10	Indicators of water supply	Frequency of water supply, water rationing, cost, coverage, quality
11	Water-borne diseases/symptoms/etiological agents	Diarrhoea, cholera, typhoid, amoebiasis, dysentery, gastroenteritis, cryptosporidium, cyclosporiasis, giardiasis, rotavirus
12	Cases of water-borne disease/symptoms/etiological agents	Lab-confirmed/self-reported/clinically diagnosed
13	Water insufficiency	Metric, proportion of urban population with sufficient water supply, proportion of urban population with insufficient water supply
14	Use of the WHO water insufficiency classification of less that 50 litres per person per day	Yes/No
15	Proportion of population with water borne diseases	Metric
16	Area proposed for future research	

(I^2) for this subset. The index of heterogeneity (I^2 statistic) will be calculated from the sum of the squared deviations of the estimate of each study, from the overall estimate, and weighted by the influence of the study on the calculation of the overall estimate. We will examine the risk bias in the study level and characterize whether the metrics of water insufficiency and health are representative of the whole urban population or only a sub-group. We will use the R statistical software (version 3.6.1) to conduct this analysis[29].

Cluster analysis will be performed to collate similar studies using Ward's agglomerative hierarchical clustering method, which is used in other scoping reviews[30]. The optimal number of clusters will be chosen to ensure the inner homogeneousness and external heterogeneousness of a cluster is balanced. For studies that focus on diarrheal disease, we will differentiate the self-reported studies from those with etiological characterisa- tion of pathogens and input these studies into the planned cluster analysis.

The study locations will be geo-coded and the data will be presented using digital maps that will depict the water sufficiency in these different cities. The results will be linked to the coordinates from the peer reviewed and publicly available water scarcity map layer from the Water Footprint Network[31] which has been used in previous systematic reviews[32]. This will allow us to make observations on the trend between cities with prevalence of waterborne diseases and water scarcity. The resultant maps will enable researchers to identify areas that have gaps in knowledge and research needs.

Ethics and dissemination

The study does not involve any interviews or interactions with humans or animals and does not require ethical approval. The findings will be published in a scientific peer-reviewed journal.

Study status

Currently, we are undertaking the literature searches in the MEDLINE, Embase, Web of Science and Google Scholar databases and extracting the titles and abstracts from the articles which will be used in the initial screening process.

Data availability

No data are associated with this article.

References

1. Dos Santos S, Adams EA, Neville G, *et al.*: **Urban growth and water access in sub-Saharan Africa: Progress, challenges, and emerging research directions.** *Sci Total Environ.* 2017; **607–608**: 497–508.
PubMed Abstract | **Publisher Full Text**
2. Cohen B: **Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability.** *Technology in Society.* 2006; **28**(1–2): 63–80.
Publisher Full Text
3. Galaitsi SE, Russell R, Bishara A, *et al.*: **Intermittent domestic water supply: A critical review and analysis of causal-consequential pathways.** *Water (Switzerland).* 2016; **8**(7): 274.
Publisher Full Text
4. Bai X: **Eight energy and material flow characteristics of urban ecosystems.** *Ambio.* 2016; **45**(7): 819–830.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
5. Alirol E, Getaz L, Stoll B, *et al.*: **Urbanisation and infectious diseases in a globalised world.** *Lancet Infect Dis.* 2011; **11**(2): 131–141.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
6. Chidya RC, Mulwafu WO, Banda SC: **Water supply dynamics and quality of alternative water sources in low-income areas of Lilongwe City, Malawi.** *Physics and Chemistry of the Earth.* 2016; **93**: 63–75.
Publisher Full Text
7. United Nations: **Sustainable Development Goals: 17 Goals to Transform our world**. 2015.
Reference Source
8. Gleick PH: **Basic water requirements for human activities: Meeting basic needs.** *Water International.* 1996; **21**(2): 83–92.
Publisher Full Text
9. African Union: **The Africa we want**. African Union Commission, 2015.
Publisher Full Text
10. World Bank and Infrastructure Consortium for Africa: **Africa's Infrastructure: A Time for Transformation**. 2010; 1–28.
Reference Source
11. UNICEF, WHO: **JMP Ladder chart**. 2017.
12. Vairavamoorthy K, Gorantiwar SD, Pathirana A: **Managing urban water supplies in developing countries - Climate change and water scarcity scenarios.** *Phys Chem Earth.* 2008; **33**(5): 330–339.
Publisher Full Text
13. IIED: **Informal Water Vendors and the Urban Poor.** *IIED.* 2006.
Reference Source
14. Lapworth DJ, Nkhuwa DCW, Okotto-Okotto J, *et al.*: **Urban groundwater quality in sub-Saharan Africa: current status and implications for water security and public health.** *Hydrogeol J.* 2017; **25**(4): 1093–1116.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
15. Bain R, Cronk R, Hossain R, *et al.*: **Global assessment of exposure to faecal contamination through drinking water based on a systematic review.** *Trop Med Int Health.* 2014; **19**(8): 917–927.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
16. GBD 2016 Diarrhoeal Disease Collaborators: **Estimates of the global, regional, and national morbidity, mortality, and aetiologies of diarrhoea in 195 countries: a systematic analysis for the Global Burden of Disease Study 2016.** *Lancet Infect Dis.* 2018; **18**(11): 1211–1228.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
17. Levine MM, Nasrin D, Acácio S, *et al.*: **Diarrhoeal disease and subsequent risk of death in infants and children residing in low-income and middle-income countries: analysis of the GEMS case-control study and 12-month GEMS-1A follow-on study.** *Lancet Glob Health.* 2020; **8**(2): e204–e214.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
18. WHO, CDC: **Integrated Disease Surveillance and Response in theAfrican Region**. 2010; 373.
19. Majuru B, Suhrcke M, Hunter PR: **How Do Households Respond to Unreliable Water Supplies? A Systematic Review.** *Int J Environ Res Public Health.* 2016; **13**(12): 1222.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
20. Gera T, Shah D, Sachdev HS: **Impact of Water, Sanitation and Hygiene Interventions on Growth, Non-diarrheal Morbidity and Mortality in Children Residing in Low- and Middle-income Countries: ASystematic Review.** *Indian Pediatr.* 2018; **55**(5): 381–393.
PubMed Abstract
21. Darvesh N, Das JK, Vaivada T, *et al.*: **Water, sanitation and hygiene interventions for acute childhood diarrhea: a systematic review to provide estimates for the Lives Saved Tool.** *BMC Public Health.* 2017; **17**(Suppl 4): 776. **PubMed Abstract** | **Publisher Full Text** | **Free Full Text**
22. Ercumen A, Gruber JS, Colford JM Jr: **Water distribution system deficiencies and gastrointestinal illness: a systematic review and meta-analysis.** *Environ Health Perspect.* 2014; **122**(7): 651–660.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
23. United Nations: **The World 's Cities in 2018**. United Nations, 2018; 34.
Reference Source
24. Peters M, Godfrey C, McInerney P, *et al.*: **Chapter 11: Scoping Reviews (2020 version).** Joanna Briggs Institute Reviewer's Manual, 2020.
Reference Source
25. Tricco AC, Lillie E, Zarin W, *et al.*: **A scoping review on the conduct and**

reporting of scoping reviews. *BMC Med Res Methodol.* 2016; **16**(1): 15.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

26. Khalil H, Peters M, Godfrey CM, *et al.*: **An Evidence-Based Approach to Scoping Reviews.** *Worldviews Evid Based Nurs.* 2016; **13**(2): 118–123. **PubMed Abstract** | **Publisher Full Text**

27. UN-DESA: **World Urbanization Prospects**. United Nations. 2014; **12**: 32.
Reference Source

28. Bramer WM, Rethlefsen ML, Kleijnen J, *et al.*: **Optimal database combinations for literature searches in systematic reviews: A prospective exploratory study.** *Syst Rev.* 2017; **6**(1): 245.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

29. R Core Team: R: **A language and environment for statistical computing**. 2017.
Reference Source

30. Fagerholm N, Torralba M, Burgess PJ, *et al.*: **A systematic map of ecosystem services assessments around European agroforestry.** *Ecol Indic.* 2016; **62**: 47–65.
Publisher Full Text

31. Mekonnen MM, Hoekstra AY: **Four billion people facing severe water scarcity.** *Sci Adv.* 2016; **2**(2): e1500323.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

32. Thomas MLH, Channon AA, Bain RES, *et al.*: **Household-reported availability of drinking water in Africa: A systematic review.** *Water (Switzerland).* 2020; **12**(9): 2603.
Publisher Full Text

Annex 4: Publications- The nexus between improved water supply and water-borne diseases in urban areas in Africa: a scoping review

Check for updates

SYSTEMATIC REVIEW

Nyamai Mutono [1-3], Jim A Wright[4], Henry Mutembei[1,5], Josphat Muema [2,3,6], Mair L.H Thomas [4], Mumbua Mutunga[3,6], Samuel Mwangi Thumbi [3,6-8]

[1]Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Nairobi, Kenya
[2]Washington State University Global Health Program - Kenya, Nairobi, Kenya
[3]Centre for Epidemiological Modelling and Analysis, University of Nairobi, Nairobi, Kenya
[4]Geography and Environmental Science, University of Southampton, Southampton, UK
[5]Department of Clinical Studies, Faculty of Veterinary Medicine,, University of Nairobi, Nairobi, Kenya
[6]Institute of Tropical and Infectious Diseases, University of Nairobi, Nairobi, Kenya
[7]Paul G Allen School for Global Animal Health, Washington State University, Pullman, USA
[8]Institute of Immunology and Infection Research, University of Edinburgh, Edinburgh, UK

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Abstract

Background: The sub-Saharan Africa has the fastest rate of urbanisation in the world. However, infrastructure growth in the region is slower than urbanisation rates, leading to inadequate provision and access to basic services such as piped safe drinking water. Lack of sufficient access to safe water has the potential to increase the burden of waterborne diseases among these urbanising populations. This scoping review assesses how the relationship between waterborne diseases and water sufficiency in Africa has been studied.

Methods: In April 2020, we searched the Web of Science, PubMed, Embase and Google Scholar databases for studies of African cities that examined the effect of insufficient piped water supply on selected waterborne disease and syndromes (cholera, typhoid, diarrhea, amoebiasis, dysentery, gastroneteritis, cryptosporidium, cyclosporiasis, giardiasis, rotavirus). Only studies conducted in cities that had more than half a million residents in 2014 were included.

Results: A total of 32 studies in 24 cities from 17 countries were included in the study. Most studies used case-control, cross-sectional individual or ecological level study designs. Proportion of the study population with access to piped water was the common water availability metrics measured while amounts consumed per capita or water interruptions were seldom used in assessing sufficient water supply. Diarrhea, cholera and typhoid were the major diseases or syndromes used to understand the association between health and water sufficiency in urban areas. There was weak correlation between the study designs used and the association with health outcomes and water sufficiency metrics. Very few studies looked at change in health outcomes and water sufficiency over time.

Open Peer Review

Reviewer Status ✓✓

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1. **Dickson W. Lwetoijera**, Ifakara Health Institute, Ifakara, Tanzania
Nelson Mandela African Institute of Science and Technology, Arusha, Tanzania
2. **Prince Antwi-Agyei**, University of Energy and Natural Resources, Sunyani, Ghana

Any reports and responses or comments on the article can be found at the end of the article.

Conclusion: Surveillance of health outcomes and the trends in piped water quantity and mode of access should be prioritised in urban areas in Africa in order to implement interventions towards reducing the burden associated with waterborne diseases and syndromes.

Keywords
water sufficiency, waterborne diseases, urban Africa, review

Corresponding author: Nyamai Mutono (mutono.nyamai@wsu.edu)

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Annex 5: Published paper: Spatio-temporal patterns of domestic water distribution, consumption and sufficiency: Neighbourhood inequalities in Nairobi, Kenya

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Nyamai Mutono [a,b,c,*], Jim Wright [d], Henry Mutembei [a,e], S.M. Thumbi [c,f,g]

[a] Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Upper Kabete, Kapenguria Road, P.O Box 30197, Nairobi, Kenya
[b] Washington State University Global Health Program, P.0 Box 72938-00200, Nairobi, Kenya
[c] Centre for Epidemiological Modelling and Analysis, Institute of Tropical and Infectious Diseases, University of Nairobi, Kenyatta National Hospital Campus, P.O Box 19676-00202, Nairobi, Kenya
[d] School of Geography and Environment Science, University of Southampton, Shackleton Building 44, Highfield Southampton, SO17 1BJ, UK
[e] Department of Clinical Studies, University of Nairobi, Nairobi, Kenya
[f] Institute of Immunology and Infection Research, School of Biological Sciences, University of Edinburgh, The King's Buildings, Charlotte Auerbach Road, Edinburgh, EH93FL, UK
[g] Paul G. Allen School for Global Health, Washington State University, P.O Box 647090-99164, Pullman, USA

A R T I C L E I N F O

Keywords:
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Urban water consumption
Sustainable development

A B S T R A C T

Whilst there are longstanding and well-established inequalities in safe-drinking water-access between urban and rural areas, there remain few studies of changing intra-urban inequalities over time. In this study, we determined the spatio-temporal patterns of domestic piped water distribution in Nairobi, Kenya between 1985 and 2018, and the implications of socio-economic and neighbourhood inequalities in water sufficiency. Using data from the Nairobi water and sewerage utility company for the period 2008-2018, we examined the sufficiency of monthly domestic water consumption per capita for 2380 itineraries (areas with an average population of 700) in relation to a residential neighbourhood classification, population and neighbourhood age and also examined water rationing patterns by neighbourhood type. Water sufficiency differed by residential areas, age of neighbourhood and population per itinerary. Compared to residents of low-income areas, those in high- and middle-income areas were six and four times more likely to receive the recommended 1500 L per capita per month respectively. Newer neighbourhoods and less densely populated areas were more likely to receive higher volumes of water. Non-revenue water loss accounted for 29% (average 3.5 billion litres per month) of water distributed across Nairobi, and was more than two times the amount of water needed for all residents to access the recommended monthly per capita water consumption. The observed spatial inequality in distribution, and access to piped water associated with socio-economic status and neighbourhood age highlights the need for deliberate planning and governance to improve water distribution to match the speed of growth of low/middle- and low-income residential areas and enhance equity.

Annex 6: Published paper: Impact of Traffic Congestion on Spatial Access to Healthcare Services in Nairobi

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Jose M. Valderas,
National University of Singapore, Singapore

REVIEWED BY
Brendan Kwesiga,
World Health Organization, Kenya
Juliet Nabyonga-Orem,
World Health Organization, Zimbabwe

*CORRESPONDENCE
Nyamai Mutono
mutono.nyamai@wsu.edu

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Impact of traffic congestion on spatial access to healthcare services in Nairobi

Nyamai Mutono[1,2,3]*, Jim A. Wright[4], Mumbua Mutunga[2,5], Henry Mutembei[1,6] and S. M. Thumbi[2,3,5,7]

[1]Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Nairobi, Kenya, [2]Center for Epidemiological Modelling and Analysis, University of Nairobi, Nairobi, Kenya, [3]Paul G. Allen School for Global Health, Washington State University, Pullman, WA, United States, [4]School of Geography and Environment Science, University of Southampton, Southampton, United Kingdom, [5]Institute of Tropical and Infectious Diseases, University of Nairobi, Nairobi, Kenya, [6]Department of Clinical Studies, University of Nairobi, Nairobi, Kenya, [7]Institute of Immunology and Infection Research, School of Biological Sciences, University of Edinburgh, Edinburgh, United Kingdom

Background: Geographic accessibility is an important determinant of healthcare utilization and is critical for achievement of universal health coverage. Despite the high disease burden and severe traffic congestion in many African cities, few studies have assessed how traffic congestion impacts geographical access to healthcare facilities and to health professionals in these settings. In this study, we assessed the impact of traffic congestion on access to healthcare facilities, and to the healthcare professionals across the healthcare facilities.

Methods: Using data on health facilities obtained from the Ministry of Health in Kenya, we mapped 944 primary, 94 secondary and four tertiary healthcare facilities in Nairobi County. We then used traffic probe data to identify areas within a 15-, 30- and 45-min drive from each health facility during peak and off-peak hours and calculated the proportion of the population with access to healthcare in the County. We employed a 2-step floating catchment area model to calculate the ratio of healthcare and healthcare professionals to population during these times.

Results: During peak hours, <70% of Nairobi's 4.1 million population was within a 30-min drive from a health facility. This increased to >75% during off-peak hours. In 45 min, the majority of the population had an accessibility index of one health facility accessible to more than 100 people (<0.01) for primary health care facilities, one to 10,000 people for secondary facilities, and two health facilities per 100,000 people for tertiary health facilities. Of people with access to health facilities, a sub-optimal ratio of <4.45 healthcare professionals per 1,000 people was observed in facilities offering primary and secondary healthcare during peak and off-peak hours.

Conclusion: Our study shows access to healthcare being negatively impacted by traffic congestion, highlighting the need for multisectoral collaborations between urban planners, health sector and policymakers to optimize health