MODELLING THE IMPACT OF VARIOUS FUTURE SCENARIOS ON UNMET WATER DEMAND USING WATER EVALUATION AND PLANNING MODEL (A CASE STUDY OF NAIROBI CITY COUNTY)

BY

ERIC SIMIYU JUMA

A Thesis Submitted to the School of Engineering, Department of Civil and Structural Engineering in Partial Fulfilment of the Requirements of the Award of the Degree of Master of Science in Water Engineering

Moi University

2024

DECLARATION

Student Declaration

This thesis is my original work and has not been presented for a degree in any other institution of higher learning.

Sign:__________________________________ Date:_____________________________

Eric Simiyu Juma

TEC/PGCS/01/14

Declaration By Supervisors

This thesis has been submitted for examination with our approval as University Supervisors

Sign:__________________________________ Date:_____________________________

Prof. Eng. Emmanuel.C. Kipkorir

Department of Civil and structural Engineering

Moi University-Main Campus

Sign:__________________________________ Date:_____________________________

Dr. Job. R. Kosgey

Department of Civil and structural Engineering

Moi University-Main Campus

DEDICATION

This work is dedicated to my dear Wife, Joy Lukamba, and my loving family. They have been with me throughout this study journey. Above all I thank God.

ACKNOWLEDGMENTS

The completion of this study was made possible by the kind support of numerous institutions and people. My two supervisors, Prof. Eng. Emmanuel C. Kipkorir and the Dr. Job R. Kosgey, deserve special recognition for their unwavering supervision throughout this masters program.

I appreciate institutions, groups, and persons who helped, by providing me with pertinent research data (billing, dam, production, map, and population data). I would especially want to thank Stanley Maina, Joab Kihamba, Peter Mironga, Benedicto Khisa, and Stanley Karani from Nairobi Water. Fred Nyongesa from the Water Resource Authority (WRA) for the advice and information sharing. I also acknowledge the MUK-VLIR UOS project and the civil and structural engineering department for providing financial assistance and the opportunity for me to pursue my MSc studies. Above all, I praise the All-Powerful God.

ABSTRACT

Nairobi city is currently experiencing both physical and economic water shortage challenges, which are caused by the city's rapid population growth, improved living conditions, dilapidated water infrastructure, and exacerbated by severe climate change impact. The management of the water shortage crisis in the city has primarily been on physical infrastructure development as opposed to the holistic water resource management approach. The main objective of this study was to apply the Water Evaluation and Planning (WEAP) model to analyse the current unmet water demand and to evaluate the effect of various future scenarios on the unmet water demand of Nairobi City. The specific objectives were; To evaluate the existing water supply and demand based on the current situation using the WEAP model; To predict the impact of population growth, improved living standards, and Non-Revenue Water (NRW) scenarios on future water demand and supply options of the city using WEAP model; and To assess the impact of introducing Rain Water Harvesting (RWH) on the unmet water demand of the city using WEAP model. The meteorological, water supply, and demand data obtained from the Kenya Metrological Department and the Nairobi City Water and Sewerage Company respectively were used to set up the model. The Soil Moisture Method embedded in the WEAP model and the monthly variation methods were used to simulate the catchment runoff and city demand respectively. The observed volume data for the Thika Dam from the year 1997 to 2016 was used for both the calibration and validation of the model. During the calibration and validation, four quantitative statistical parameters were used to check the performance of the model to represent the catchment. The coefficient of determination (R^2), Nash Sutcliffe (NSE), Standard deviation of measured data (RSR), and the Percentage Bias (PBIAS) values were 0.70, 0.98, 0.13, and 4.9 respectively for calibration and 0.74, 0.98, 0.15, and 9.1 for validation. After the model setup, a reference scenario was created to represent the current water supply system and project it to the study period of 2021 to 2040. Future Scenarios were then built from the reference scenario. Two socioeconomic transformation scenarios were developed to examine the impact of rapid population increase and rising standards of living. The results in the reference scenario showed that the city would only satisfy 19% of its water needs by 2040 with an unmet water demand of 948 million cubic meters. The population growth will increase the unmet water demand to 1,036 million cubic meters by 2040, while the improved living standard will increase it to 1,309 million cubic meters in the same year. On the contrary, the reduction of non-revenue water and the introduction of rainwater harvesting will have a significant positive impact on the unmet water demand. The unmet water demand will be 624 million cubic meters and 822 million cubic meters by 2040 for non-revenue water reduction and rainwater harvesting scenarios respectively. Based on these results, it was concluded that the WEAP model can assist the water utility in making decisions that will improve water service delivery within the city. The water utility should adopt rigorous non-revenue water reduction strategies while the county government should put in place relevant legislation to operationalize rainwater harvesting.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABREVIATIONS

AWSB - Athi Water Services Board.
DC - Deep Zone Conductivity
DMS - Demand Management Strategy
DN - Nominal Diameter
DSS - Decision Support System
DWC - Deep Water Capacity
EFR - Ecological Flow Requirement
FAO - Food and Agriculture Organization
GIS - Geographic Information System
GoK - Government of Kenya.
GUI - Graphic User Interface
GWP - Global Water Partnership
IWRM - Integrated Water Resource Management
K_c, - crop coefficient
KNBS - Kenya National Bureau of Statistics
LIA - Low-Incomee Areas
NCIDP - Nairobi County Integrated Development Plan
NCWSC - Nairobi City Water and sewerage Company
NRW - Non- Revenue Water
PEST - Parameter Estimation Tool
PFD - Preferred Flow Direction
PS - Pumping Station
RRF - Runoff Resistance Factor
RWH - Rain Water Harvesting
RZC - Root Zone Conductivity
SDG - Sustainable Development Goals
SEI - Stockholm Environment Institute
SWC - Soil Water Capacity
UNDESA - United Nations Department of Economic and Social Affairs

WARMA	-	Water Resource Management Authority
WASREB	-	Water Services Regulatory Board
WEAP	-	Water Evaluation And Planning
WRA	-	Water Resource Authority
WSP	-	Water Service Provider
WWAP	-	World Water Assessment Programme
Z1	-	Upper Zone layer
Z2	-	Lower Zone layer

CHAPTER ONE: INTRODUCTION

1.1 Background

Water scarcity is becoming a global challenge that needs immediate attention. This challenge, according to Nabinejad. et al. (2017), is accelerated by the increasing water demand occasioned by the growth in population, deteriorating water quality, and loss of freshwater due to water management inefficiencies.

According to World Water Development Report (WWAP, 2018), the global population growth is expected to increase from 9.4 to 10.2 billion people by the year 2050, this will have a corresponding increase in the water demand in agriculture, industry, and domestic use. The majority of this growth will be in Africa where it is estimated that the biggest increase will occur, with over 1.3 billion, of the present value (UNDESA, 2017).

In Africa, inadequate management of water resource and infrastructure contributes to the pronounced poverty levels in Sub-Saharan Africa. According to Matango (2019), Africa not only faces challenges in satisfying the demand for clean water and access to sanitation for this rapidly expanding population, but also rising demand for energy, food, jobs, healthcare, and education. The majority of the population growth takes place in urban areas, and if not properly planned for, could result in a sharp rise in slums which would exacerbate the already difficult access to water and sanitation services (WWAP, 2018).

The Kenya National Water Master Plan of 2013 (NWMP, 2013) predicted that by 2030, there would be 46 million people living in urban centres, up from 13 million in 2010. Water Services Regulatory Board (WASREB) in 2018 presented a national drop in average daily service hours from 18 hours to 14 hours which was attributed to the drought experienced in the year 2017 and other effects of climate variability. This suggests that to attain Sustainable Development Goals (SDG) the country should put in place resilient water systems ((WASREB, 2018). The water resources in the urban areas should be managed prudently, to meet the potable water needs of the demand population without having an adverse impact on the environment.

The growth in urban centres and especially cities has a corresponding increase in population, this is because urban centres need the human resources and labour force while people are attracted to the economic activities that come along with the growing cities (Haughton & Hunter, 2004). Nairobi City, the largest city in Kenya and a regional commercial hub, has seen significant growth in population over time. The population of the city makes up 9.2% of Kenya's total population. Its population increased from 3.1 million in 2009 (KNBS, 2010) to 4.4 million in 2019 (KNBS, 2020). which is almost an increase of 30%. This population growth has a proportionate impact on the unmet water demand of the city.

1.2 Problem Statement

Industrialization, increased population, and climate variability are factors putting cities on the fast lane to scarce freshwater resources in the future. There is need to control and limit the impact of urban households on environmental footprint (Shuetze & Fandino, 2013). Nairobi city is experiencing water supply problems with an installed water supply capacity of 525,500 m^3/day against a water demand of 864,000m^3/day in 2019. This translates to an unmet water demand of approximately 338,500m^3/day (Nairobi water, 2019), the company further projects a water demand of above 1,000,000m^3/day by the year 2024 (Nairobi water, 2019). The situation is made worse by the water service provider`s considerable levels of system inefficiencies, which lead to high non-revenue water levels. The unmet water demand is expected to go up if there are no deliberate efforts to arrest the crisis. Therefore, Nairobi City Water and Sewerage Company (NCWSC) which is the sole water service provider to the city, requires to put in place mitigation measures and establish several water interventions to tame the growing unmet water demand. To address this challenge, the study envisages developing a water supply-demand model that will assist the water utility in assessing supply and management options to address the water demand of the city.

1.3 Justification of the Study

The aim of this study was to clearly illustrate the relationship between supply and demand in a model that can analyse the current and future water demands of Nairobi City and recommend water supply and management strategies to address the unmet water demand within the city. Computer-based Decision Support Systems (DSS) are used to estimate and evaluate the effects of various water supply and management initiatives on the unmet water demand and demand coverage. In this study Water Evaluation and Planning (WEAP) model was applied in scenario formulation, planning, and management. WEAP approaches water resources planning from an integrated water management perspective (SEI, 2011). Stakeholder participation in the modeling process is simple thanks to its transparent structural system. It is appropriate for this research since it focuses on policymaking rather than just hydrological facts. By developing future scenarios, the WEAP model can be used to evaluate various management decisions and ascertain their long-term effects on the organization.WEAP stands out for its integrated approach to modeling both the artificial and natural components of water systems. This provides the user with a more comprehensive understanding of the numerous elements that must be taken into account while managing water resources for both present and future uses. The results of this research can be used by the water utility for planning and putting in place the mitigation measures to tame the growing unmet water demand. The county government can also adopt the alternative water supply options from the results of this research and put in place relevant legislation to promote the proposed supply intervention.

1.4 Study Objectives

1.4.1 Main objective

The main objective of this study was to analyse the current unmet water demand of Nairobi city and to evaluate the future effects of population growth, high living standards, Non-Revenue Water levels, and supply interventions on water supply and demand using Water Evaluation And Planning (WEAP) model.

1.4.2 Specific objectives

i. To evaluate the existing water supply and demand based on the current situation using WEAP model.
ii. To predict the impact of population growth, improved living standard, and Non-Revenue Water (NRW) scenarios on future water demand and supply options of the city using WEAP model.
iii. To assess the impact of introducing Rain Water Harvesting (RWH) on the unmet water demand of the city using WEAP model.

1.5 Research Questions

This research is guided by the following questions:

i. What is the existing water supply and demand of Nairobi city?
ii. To what extent does the future water supply and demand scenarios affect the unmet water demand?
iii. How will the proposed water Rain Water Harvesting affect the unmet water demand?

1.6 Structure of the Thesis

The thesis is organized into five chapters; The first chapter introduces the background of the thesis, the problem statement, the justification for the study, and the study objectives. The second chapter provides the Literature review of integrated water resource management models, a review of the literature on the WEAP model is also presented, and finally, the application of WEAP in different countries with more bias to urban water management is reviewed. The third chapter discusses the methodologies and practices used in this research. The hydrological and demographic characteristics of the study area, data preparation, model calibration, validation, sensitivity analysis, modeling procedures, and scenario creation. The fourth chapeter presents the results and discusses the impact of several future scenarios on the unmet water demand of the city and the demand coverage. For this study the impact of management and external driven scenarios were analysed. Under the management scenario, rainwater harvesting and non-revenue water was considered while for the externally driven scenario the population growth and the living standard were analysed. The results in this chapter were used to project the future water situation of Nairobi city. Finally the fifth chapter presents the study conclusions for the water supply system of Nairobi City based on the results of model simulations on specific objectives. The recommendations are thereafter done on the short-term and long-term water plans to improve on the city water situation.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Physical infrastructure development received most of the attention in the water sector as opposed to the holistic water resource management approach (Abdo, 2009). Planning water allocation remains a daunting task for water planners within the region, as priority is given to enhancing infrastructure to satisfy the demands of a growing population, and a growing economic sector. Using an integrated approach in modelling helps in attaining social justice, environmental and financial sustainability in water management, this in turn increases the effectiveness of water use while making it easier to identify and execute appropriate solutions (Abdo, 2009).

This chapter introduces the background knowledge on water management models, and then discusses the different hydrological models. After that, the WEAP model will be introduced in detail based on the publications on the WEAP website. Finally, a discussion of the application of the Water Evaluation and Planning model at both the global and local levels will be provided, with a focus on its application in urban water management.

2.2 Water Resource Management Models

No single hydrological or Integrated Water Resource Management (IWRM) model stands out when it comes to water management (Aung, 2014). Models are categorized based on their geographical scale and physical detail to make it possible to choose the best model for a given problem. Figure 2.1 shows that Podium, STREAM, SLURP, and WSBM are national-scale IWRM models, SWAT and WEAP are IWRM models for basin and system analysis, while SWAP, WaterMod, and FutureView are small-scale IWRM tools (Immerzeel & Droogers, 2008). A few of the models are briefly discussed below.

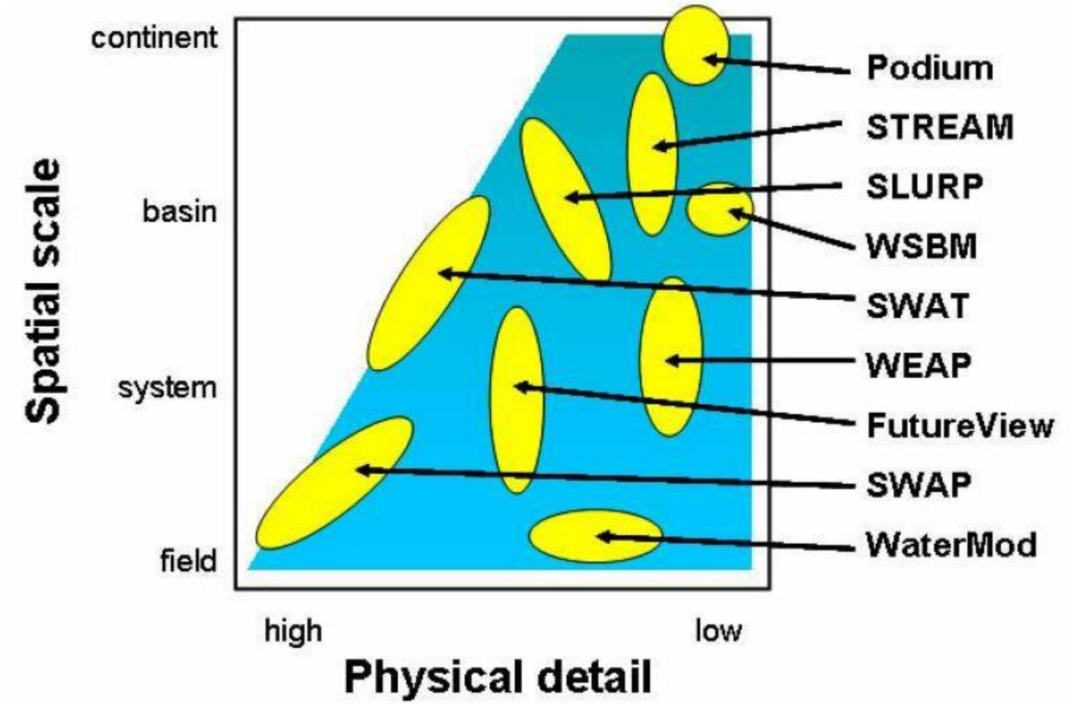


Figure 2.1: Model hydrological details (Immerzeel & Droogers, 2008)

2.2.1 MULINO DSS

MULINO DSS is a Decision Support System software (DSS) applied at a catchment scale for the holistic management of water. The model integrates geospatial data, and multiple criteria analysis with socioeconomic and environmental as the basis for modelling (Giupponi et al., 2004). In this model the end user chooses the algorithms for decisions making rules based on the value functions and weights parameters then the model integrates them and provides the optimal quantitative indicators to be used for decision- making.

2.2.2 MIKE BASIN

This is a hydrologic model embedded with ArcGIS to simulate and visualize water allocation, conjunctive use, reservoir operation, and water quality challenges to offer basin-scale solutions in water management (Aung, 2014). The model is based on a network where the nodes represent confluences, diversions, reservoirs, or water users and the branches represent specific stream sections (Mugatsia, 2010). This is a river flow routing model which is assumed to be a quasi-steady-state mass balance model. It uses a linear reservoir equation for the ground-water analysis (Loucks, 2006). To implement an integrated catchment management system, the model is linked to hydrological models like NAM or MIKE SHE (Aung, 2014).

2.2.3 MODSIM DSS

Colorado State University created this generalized river/reservoir system and network flow model to mimic priority-based water allocation (Loucks, 2006). The model incorporates the database management subsystem, dialog generation and management subsystem, and model base management subsystem. All crucial elements of a decision support system are built into MODSIM. An effective network flow optimization model and numerous database management components are linked to MODSIM by the Graphical User Interface (GUI) (Schnier, 2010). The model may be used in conjunction with groundwater models to examine the usage of surface and groundwater simultaneously, water quality models to evaluate pollution control strategies, and Geographic Information Systems (GIS) to manage geographic data.

2.2.4 HEC-ResSim

According to Yates et al. (2005), HEC ReSim is a reservoir simulation model, that depends on prescribed flows from other models to specify operating criteria such as release needs, limitations, hydropower requirements, and numerous reservoir operations.

2.2.5 The River Basin Simulation Model (RIBASIM)

This is a hydrological model that analyses a variety of hydrological scenarios at the river basin scale (Ramadan et al., 2011). It was created in 1985 at the Dutch company

Deltares. The model package is a flexible and comprehensive tool that links the hydrological inputs at various sites with the distinctive water users in the basin. Users can evaluate a variety of infrastructure, operational, and demand management-related measures using the RIBASIM model, and then look at the results in terms of water quantity, water quality, and flow composition (Ayele, 2016). The model may also produce flow patterns that serve as a foundation for thorough evaluations of sedimentation and water quality in river reaches and reservoirs.

2.2.6 WEAP (Water Evaluation And Planning System)

WEAP model is an IWRM model designed to bridge the gap between water management and watershed hydrology while also satisfying the requirements that an effective IWRM must be practical, easy to use, affordable, and widely available to the entire water resource community (Yates et al, 2005). A variety of physical hydrologic processes are seamlessly and coherently integrated into management requirements and built infrastructure by WEAP. The model enables the examination of many scenarios, including alternate climate scenarios and shifting anthropogenic stresses such as land-use changes, shifting societal and industrial demands, shifting operating procedures, and points of divergence. WEAP is efficient, practical, simple to use, reasonably priced, and easily accessible. It may also analyse a variety of scenarios, including climate change and other changes like technology, social-economic, and policy advancements for example changes in land use, changes in industrial and municipal demand, and adjustments to operational procedures. The main objective of WEAP is to deal with issues and challenges surrounding water planning and resource allocation, but it may also examine water quality, cost-benefit analyses, and hydropower based on hydrological processes (Aung, 2014).

2.3 WEAP MODEL

WEAP is an object-oriented computer modeling program and IWRM tool that was developed by the Stockholm Environmental Institute to simulate the water supply system and analyse the water demand. The Model also serves as a testing ground for alternative water management and development plans (SEI, 2011). WEAP model functions according to the fundamentals of water balance accounting (SEI, 2011). It applies to both straightforward river systems and those with several sub-basins. By considering both the supply and demand sides of the water balance equation, it employs an integrated approach to simulate water systems. The model enables the investigation of alternative water development and management techniques. On the demand side, WEAP takes into account water consumption patterns, the demand for hydropower, the efficiency of the equipment, and allocation priorities.

On the other hand, WEAP takes streamflow, groundwater, reservoirs, and water transfer into account on the supply side. WEAP can also cover water rights, reservoir operation, ecosystem requirements, project cost-benefit analysis, and water conservation (SEI, 2011). The research area in WEAP reflects the configuration of the water resources system and its elements, and it also contains information and suppositions about the system. The system is made up of interconnected demands and supplies (rivers, reservoirs, groundwater aquifers, demand nodes). Several separate research areas may reflect the same geographic area or watershed in different configurations, with various sets of demand data, or with various operating hypotheses. The research regions might be compared to databases that are used to store, manage, and analyze various sets of data related to water supply and demand.

The supply and demand information for the first year of the study is included in the Current accounts, which represent the concept of the water system as it is currently understood. Additionally, it is believed that all scenarios begin in the year of the current accounts. The Current Accounts and Reference scenario (also known as the business-as-usual scenario), must be developed before creating any alternative policy scenarios in WEAP for comparison with the reference scenario (SEI, 2011). The reference scenario depicts the existing state of policy, supply and demand for water, economic, demographic development, and other issues without any other alterations.

WEAP can also depict how demand management impacts on water systems, for example, how water price policies impact on water demand (SEI, 2011). WEAP scenarios make predictions about upcoming laws, developments, and other elements that will impact supply and demand. To determine the amount of water demand, scenarios can be created and then compared. Every scenario begins with the same established current account year. WEAP scenarios may include any variable that is subject to change over time, such as variables that reflect various socio-economic assumptions. Once the study area is described for current accounts and the scenarios are defined for chosen time horizons, the model calculates the water balance and allocates it to each system component (river reach, reservoir, aquifer, and demand).

The findings allow for evaluation of the scenarios' water sufficiency, compliance with environmental goals, costs, benefits, and sensitivity to uncertainty in important variables (SEI, 2011). WEAP model is flexible and can be linked to most water related models like QUAL2K which is a model for water quality, MODFLOW for modelling ground water flow, MOD-PATH embedded in MODFLOW for particle tracking, Parameter Estimation Tool (PEST) and General Algebraic Modeling System (GAMS), Excel, and Google Earth (SEI, 2011).

2.3.1 Scenario management

Scenario analysis is carried out in the WEAP model based on the "What-If" question in order to analyse current trends and alternative scenarios with changes on both the demand and supply sides, and it is evaluated by comparing the "business as usual"/reference scenario to the actual data (SEI, 2011).

2.3.2 Application of the WEAP model

By taking into account several scenarios, Leong and Lai (2017) used the WEAP model to assess the current and future water management system in the Langat River basin in Malaysia. The Catchment and the associated demand points were taken into account by the authors when building the model. They divided the catchment into 10 sub-hydrological catchments and 17 demand sites to make up the hydrological model used in the study. Three scenarios were used to examine the supply and demand trends in the watershed up to 2050: the population growth rate, demand-side management (DSM), and a combination of DSM and a decrease in non-revenue water (NRW). According to the results, combining the demand side management with lowering Non –Revenue Water greatly lowers the unmet water demand.

Aung (2014) created a model for the Yangon City Water Supply System (YCWSS) using the Water Evaluation and Planning System (WEAP) modelling software. The model was used to analyse the existing state of the water supply system as well as the effects of various externally driven alternatives and management options, with a primary focus on the coverage of Yangon City's water demand. Three socioeconomic change scenarios were created using data from a global climate model to examine the effects of rapid population growth, moderate population growth, and greater living standards, and a climate change scenario. In order to analyse how management practices, affect both the supply and demand sides, four management strategy scenarios were designed.

The study demonstrated that the WEAP model can be utilized to establish strategic development choices for the YCWSS to adapt to future possibilities and can also support Yangon City's water management and local authorities in making decisions for the improvement of the YCWSS.

Abdo (2009) used the WEAP model to evaluate the management strategies being used by Nablus City to address its water crisis. The findings indicated that the unmet water demand would rise over the coming years. The main cause of this was the rising population in areas with scarce water supplies. To minimize the raising water demand, the study proposed an alternative water supply as a remedy. In comparison to spring restoration, the study found that storm water collecting would be a better solution for reducing the unmet water demand.

The WEAP model was used by Malla et al. (2014) to evaluate the water supply and demand in the Indian city of Srinagar. Dachigam Stream and Sindh Stream discharge data from 1979 to 2010 were used in the study as supply to the demand sites and to determine the effects of changing climatic conditions on them. The model produced discharge patterns for the study rivers over a 15years period as well as scenarios that calculated future supply and demand. The model's findings indicated that future water shortages were anticipated. The results of the model outputs were used to make predictions about whether the available water supplies will be enough to meet the expanding water needs.

By integrating a scenario analysis method in the WEAP model, Arranz and McCartney (2007) evaluated the effects of potential water demands on the Olifants catchment's water supplies by 2025. Olifant is One of South Africa's 19 watershed management areas. The catchment is home to a variety of water users, including rural, urban, mining, subsistence, and commercial irrigated agriculture, commercial forestry, industrial, and power generation. The effects on water resources under each scenario were compared to a 1995 "baseline". Abdo (2009),

For each scenario, the model allowed for analyses of unmet water demands, stream flows, and water storage. The output of the model demonstrated that, for the various study scenarios, implementing the environmental reserve will result in more shortages in other sectors. Combining the Department of Water Affairs and Forestry's major water storage infrastructure proposal with measures for water conservation and demand management, it is possible to achieve levels of unmet demand and deficits that are lower than or comparable to those observed in the 1995 baseline.

In the study of water resources and municipal sustainable development of Heng Shui City in China, Zaccheaus (2006) used WEAP as an urban water management tool. This study investigated and assessed future scenarios involving rapid population growth, advanced technology, and demand management. It did so using the water year approach, demand disaggregation, and supply preferences. The study explicitly stated that the data's accessibility and dependability were crucial and needed to be thoroughly and wisely analysed. It was also noted that the implementation of water demand management was seen to present opportunities during normal hydrological years but not in dry years.

Ayele (2016) used the WEAP model to estimate future water demands and the water balance of the Caledon River basin in South Africa. The modeling outcomes demonstrated that rapid population growth exacerbates the water deficit in all catchment water consumption sectors. In the case of rapid population growth, the unmet demand happened between May and October. However, according to irrigation and Environmental Flow Requirement (EFR) scenarios, the unmet water demand only materialized from June to September. In a scenario with rapid population growth and when the population growth rates are changed, the annual unmet demand would significantly rise beyond 2020. The irrigation sector's demand is met, or no unmet needs were noted in any of the years. The result showed that the river flows would meet the projected demand in 2025. However, most rivers, including the main river (Caledon River), will not be able to meet.

WEAP was used by Osoro et al. (2018) to model supply and demand in the Mara River Basin. By using 2010 as the reference year for the modeling scenarios up to 2045, the water usage and resources in the basin were quantified and mapped in terms of their present and future conditions. The model was calibrated using the Parameter Estimation Tool. According to the findings, the basin's overall water demand was 4.91 BCM under the reference scenario, 4.1 BCM under the Demand Management Strategy (DMS) scenario, and 3.5 BCM under the scenario combining an enhanced policy implementation and DMS. The findings also indicated that by lowering water demands at the basin, the planned DMS might improve water sustainability.

Okungu et al. (2017) evaluated the historical water supply in the Yala basin and simulated the anticipated future water demand within the catchment using the WEAP model (the year 2016 to 2045). WEAP simulations were run for four different scenarios, including the reference scenario (with a population growth rate of 2.8 percent), the high population growth scenario (3.5 percent), and the moderate population growth scenario (2.2 percent). Results showed that the Domestic-Institutional-Municipal demand category would receive 66.9% under the reference scenario. Contrarily, the supply requirements for the categories of agriculture and industry were proportionately distributed over the simulated period and needed 30,.3% and 2.8% of the total supply requirements, respectively. The distribution of water, however, varied between demand sites based on the relative priorities of the various demand categories. The study suggested using supply and demand strategies to control activity.

In order to integrate water management of the Nyando river basin in Kenya, Dienya (2007) applied the WEAP model. The study's findings showed that the basin has a significant unmet water demand. Estimates placed the entire Unmet Water Demand at 15.33 MCM. With two dams in place, the ecological flow requirement was not satisfied at its maximum in January, when it was 5.0 MCM during exceptionally low flows. The entire unmet irrigation water demand would be 482 MCM if basin irrigation were expanded to its maximum extent. According to scenario analyses, the three proposed dams will allow Ahero and South West Kano to fully realize their irrigation potential, increasing it from their present 1,600 ha to 25,000 ha.

Mugatsia (2010) used the WEAP model to analyse and simulate several scenarios for managing water resources in the Perkerra catchment. The results showed that the flow time series will peak extremely sharply downstream and be highly vulnerable at the demand nodes, with demand coverage varying between 10% and 100%. The flow would be stabilized and the demand coverage would increase to between 60% and 100% with the construction of two dams (Chemususu and Radat). However, the average demand coverage downstream falls to between 45% and 100% with the implementation of environmental flows and water supply projects downstream of station 2EE7B. It would be possible to deliver 13,000 m3/day of water to nearby communities and enhance the amount of water available for cultivation by 90% thanks to the improved storage (by two dams). This analysis, however, assumed proper regulation of abstraction and reservoir operations.

The WEAP model was used by Nyika et al. (2017) to forecast demand and analyse potential water use scenarios in the Mbagathi sub-catchment. The model design was configured to create reference and current scenarios. When compared to reduced conveyance losses and greater reservoir capacity, reuse was deemed by the model to be the most effective way to handle unmet needs as a result of the high population growth and protracted drought. The study concluded that using wastewater for water reuse could be a practical way to address the water issues in the Mbagathi sub-catchments.

The current study considered four future scenarios and ran simulations based on changes in population growth, changes in city residents' living standards due to economic growth, reduced non-revenue water and suggested alternative water supply interventions to better understand the impact of external and management factors on the future water supply system of Nairobi city.

2.3.3 The research gap

Most of the literature has mentioned a lot on the augmentation of supply for Nairobi to meet the rising demand. This has informed the government's decision on the proposed supply interventions to increase the water supply within the city. There exists very little research on the management of water through demand-side management and the utility operational efficiency as an alternative to meeting the ever-increasing unmet water demand. This research seeks to fill this gap by looking at the water utility non-revenue water, demand side management, and proposing alternative water supply to the city.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

This chapter presents the methodology adopted in the study. Its primary emphasis is on conceptual modelling procedures, scenario development, input data preparation, and the hydrological and demographic aspects of the study area and catchment. The WEAP model was utilized to evaluate the current water supply system of the water service provider and to predict future water supply scenarios. The model took into account several variables and policies that could have an impact on future water demand and supply alternatives.

The future years of 2022 to 2040 were examined under four scenarios: Increased population growth, management of non-revenue water, an improvement in living standards; and implementation of Rain Water Harvesting (RWH). The base year was set to 2021. The analytical conceptual methodological framework is shown in Figure 3.1.

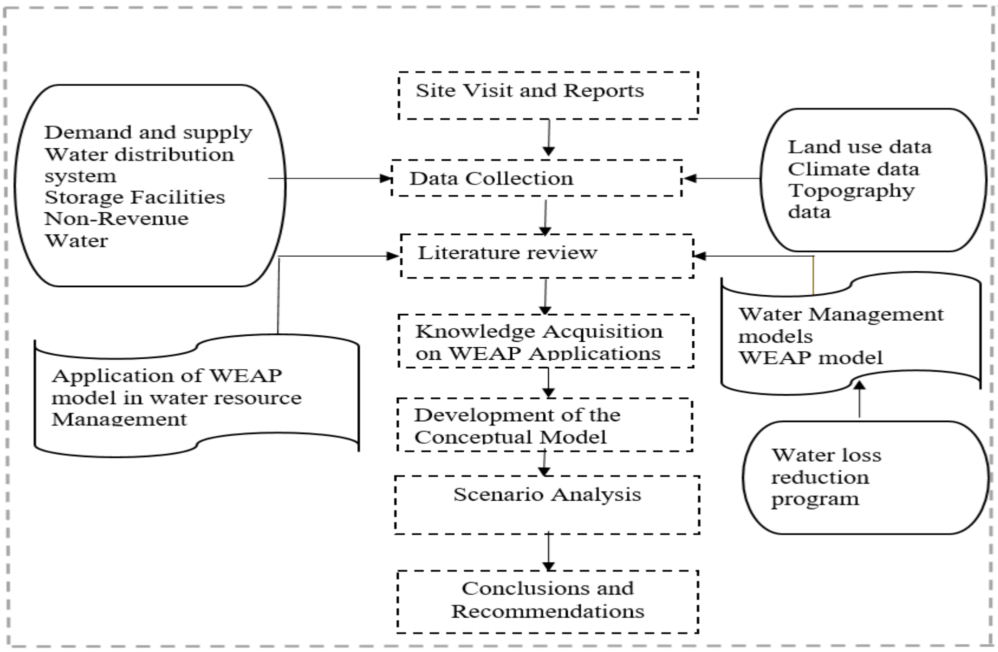


Figure 3. 1 Conceptual methodological framework of WEAP

3.2 Description of the Study Area

3.2.1 Location

here are 47 counties in the Republic of Kenya, with Nairobi City County being one of them (Figure 3.2). Nairobi city shares borders with Machakos to the east, Kajiado to the south, and Kiambu County to the north and west. Kiambu County's border with Nairobi County is the longest among the three neighbouring counties. The county has a total size of roughly 696.1 km^2 and is located between the longitudes of 36^o 45" East and latitudes of 1^o 18" South. On average, it is 1,798 meters above sea level (NCIDP, 2014).

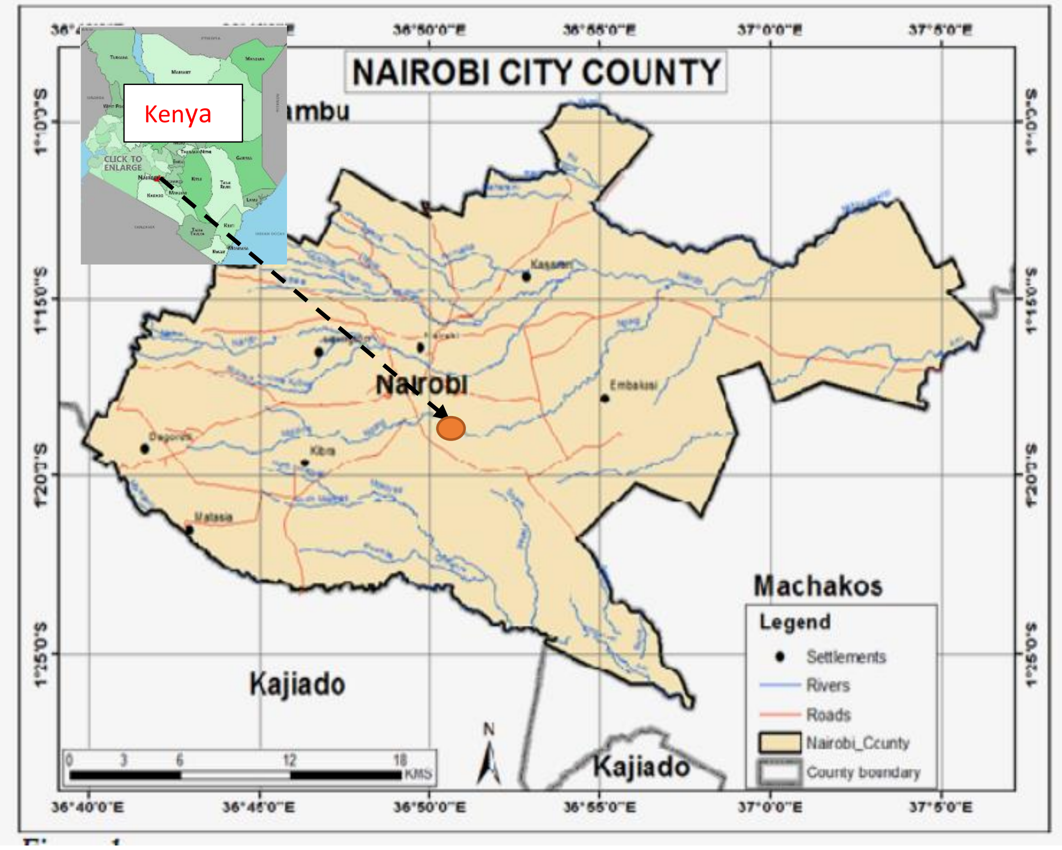


Figure 3.2: Location of the Study area (Source: Ndolo, et al 2017)

3.2.2 Topography and climate

The topography of the study area shows a general eastward slope as it descends from 2,000 meters above sea level in the west to 1,600 meters above sea level in the east. The most notable topographical features of the Nairobi region are the Ngong Hills, which are situated to the west of the city. This County is traversed by the Nairobi River and its tributaries. Nairobi County is 1,798 meters above sea level on average. Evenings are cool due to the altitude, especially in the months of June and July when lows of 10 °C are common. The short rainy season spans from October to November, whereas the long rainy season lasts from April to June. The bright and sunny months of the year, from August to September and December to March, have average daytime temperatures in the mid-twenties. Nairobi has a subtropical highland climate, with little seasonal variation due to its proximity to the equator (Muraguri, 2013).

3.2.3 Population

Nairobi is among the rapid-growing cities in Africa. Due to high birth rates and rural-urban immigrants who move to Nairobi in search of employment, the city's population is rising at a pace of about 3.8 per cent per year. Table 3.1 displays the population trend from 1948 to the most recent 2021. The current projection for Nairobi's population in 2021 is 4,737,600.

Table 3.1: Nairobi Population Trend (KNBS 2019, Mitullah 2003)

Year	Area (ha)	Population	Pop.Density (Persons /ha)
1948	68,945	118,976	2
1963	68,945	342,764	5
1969	68,945	509,286	7
1979	68,945	827,755	12
1989	68,945	1,324,570	19
1999	68,945	2,143,284	31
2009	69,510	3,138,369	45
2019	70,390	4,397,073	62
2021	70,390	4,737,600	67

3.2.4 Water supply

a) Water sources

The Sasumua Dam, Thika Dam, Ruiru Dam, Kikuyu Springs, and Boreholes are the main water sources in Nairobi City. Table 3.2 gives a summary of the water supply's capacities. Figure 3.3 displays the general layout of Nairobi City's water supply. According to estimates, Nairobi's boreholes add an extra 58,685 m^3/day to the water supply grid.

Table 3.2: Existing Water Sources for Nairobi City (Source: Nairobi water, 2019)

Name	Water supply Capacity (m^3/day)	Type of raw water source
Sasumua Dam	59,000	Chania River
Thika Dam-Ngethu	440,000	Thika river
Ruiru Dam	21,700	Ruiru River
Kikuyu Spring	4,800	Two springs
Boreholes	58,685	Boreholes
Total	**584,185**	

b) Existing Water Supply Facilities

Nairobi City has four different water delivery systems: The Sasumua, Ruiru, Mwagu, and Kikuyu spring systems (Nairobi Water, 2019). The Sasumua Water Treatment Plant (WTP) and Ngethu Water Treatment Plant (WTP) have raw and treated water transmission pipelines that are located outside of Nairobi City. Along its network, Nairobi City Water Supply and Sewerage Company (NCWSC) delivers bulk to the local Water Service Providers (WSP) along the water transmission lines.

c) The distribution network

The four primary reservoirs that Nairobi City uses to supply its distribution system with treated water are the Kabete, Kyuna, Kiambu, and Gigiri reservoirs. Based on the reservoir that each zone receives water from, the distribution area is divided into 13 zones. The distribution network is set up with a high density in Nairobi City's Western region and a low density in the Eastern region. Figure 3.3 depicts the general layout of Nairobi's water supply (Nairobi water, 2019).

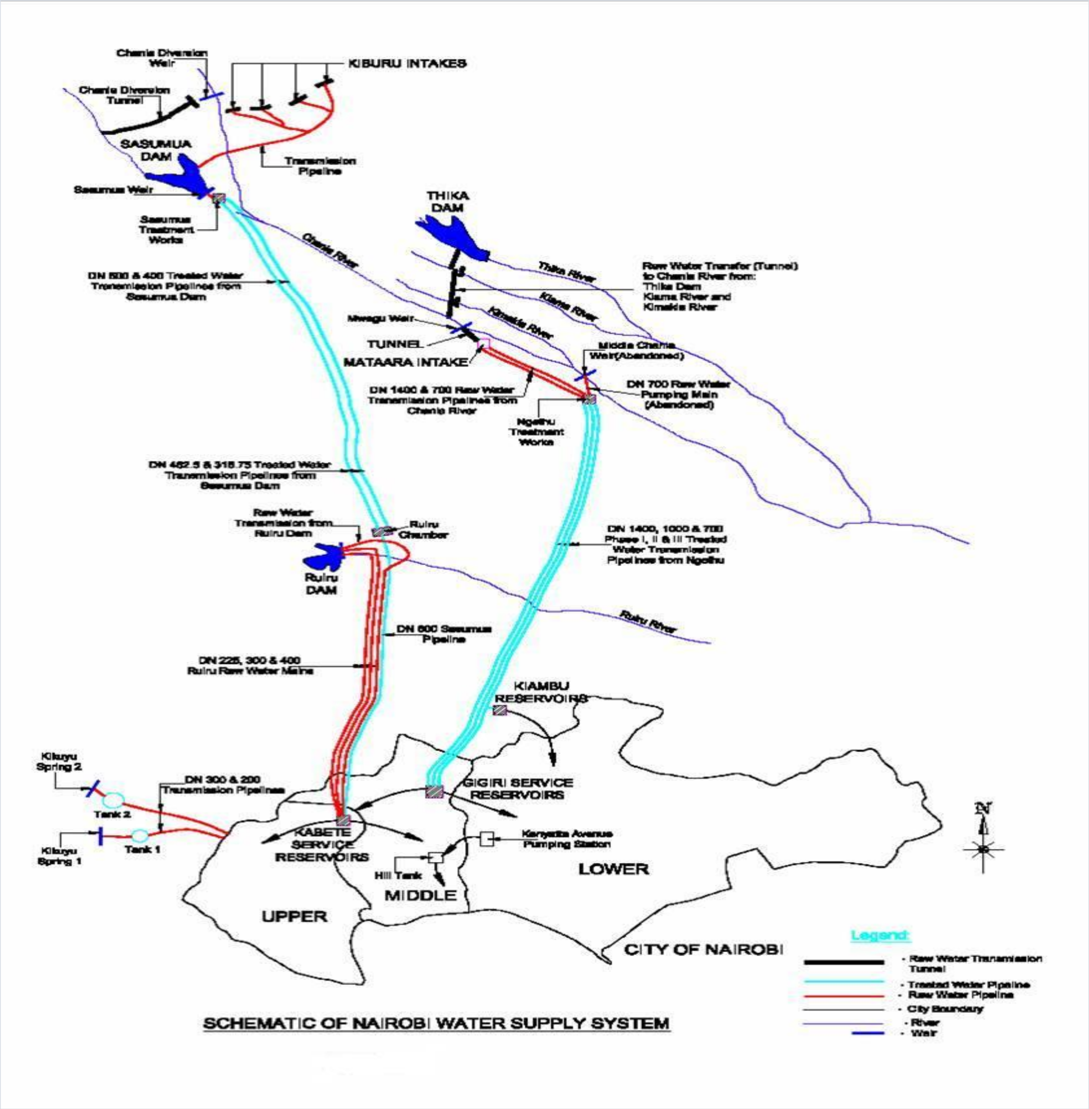


Figure 3.3: Outline Map of Water Supply to Nairobi City (Source: JICA, 2014)

3.2.5 Non-Revenue Water

Nairobi City Water and Sewerage Company (NCWSC) adopted International Water Association (IWA) water balance matrix in reporting its non-revenue water. The annual water production for the year 2021 was estimated at 179.3Mm^3 while the annual billed volume minus billing from borehole volumes was 92.9Mm^3. This brings the estimated Non-revenue water to 48 %. Water supply to some of the growing informal settlements, aging infrastructure, and unauthorized water connections are some of the factors contributing to the high non-revenue water percentage. The cooperate strategic plan of

2019/2020-2023/2024 (Nairobi Water, 2021) for Nairobi city water and sewerage company, envisages reducing NRW from 48% to 25% by the year 2025.

Table 3.3 : Non-Revenue Water Figures (Nairobi water, 2021)

	Year				
	2017	**2018**	**2019**	**2020**	**2021**
Production (Million M3)	181.4	172.9	180.2	176.0	179.3
Billed Volume (Million M3)	112.8	106.9	114.6	90.1	92.9
Non-Revenue water (%)	**38%**	**38%**	**36%**	**49%**	**48%**

3.3 WEAP Modelling

3.3.1 Introduction

WEAP is a vital tool for planning water resources that consider not only water supply-side and water demand-side issues but also water quality and ecosystem preservation challenges due to its integrated approach to simulating water systems and its policy orientation (SEI, 2011). This model was used to assess and predict water development and possible management scenarios for the future. The model replicates the operation of the city's water supply system on a user-defined time step, computing the water mass balance for all WEAP nodes and lines, components of the water system, and linkages of these components (SEI, 2011). Using the results from the WEAP program, policymakers and water supply authorities can develop suggestions for future water supply and demand management. The following steps are often included in a WEAP model application (SEI, 2011):

i. Establishing the Study Definition, which specifies the problem's configuration, time frame, system components, and spatial boundaries.

ii. Data entry in the current accounts, which provides an overview of the system's present status which sometimes can be viewed as the calibration stage of the model.

iii. Developing key assumptions for the current accounts that represent the regulations, expenses, and elements that influence demand, pollution, supply, and hydrology.

iv. Creating scenarios on current accounts that can be investigated in terms of how different options may affect future water supply and demand.

v. Evaluating scenarios, considering water demand coverage and unmet water demand.

In order to make the NCWSC's schematic representation as accurate as possible and as simple as possible to understand, both the demand and supply sources are specified in detail. Due to the fact that these components are unaffected by the scenario analysis for the entire city and the WEAP model simulation, unnecessary components like service water tanks and pumping stations are not included in the schematic.

Referring to Figure 3.4, the model schematic of NCWSC, this WEAP model consists of the following WEAP objects: 5 Catchments, 7 Reservoirs, 1 Groundwater Source, 6 source rivers, and 3 Diversion, 11 Transmission Links, 1 Demand Sites, 2 Waste Water Treatment Plant, and 4 Return Flows and Rainwater Harvesting virtuel node. The systematic procedure for the development of the model and the entry data analysis of NCWSC will be expressed in subsequent sections. Figure 3.4 is a model schematic representation of NCWSC demand and supply system.

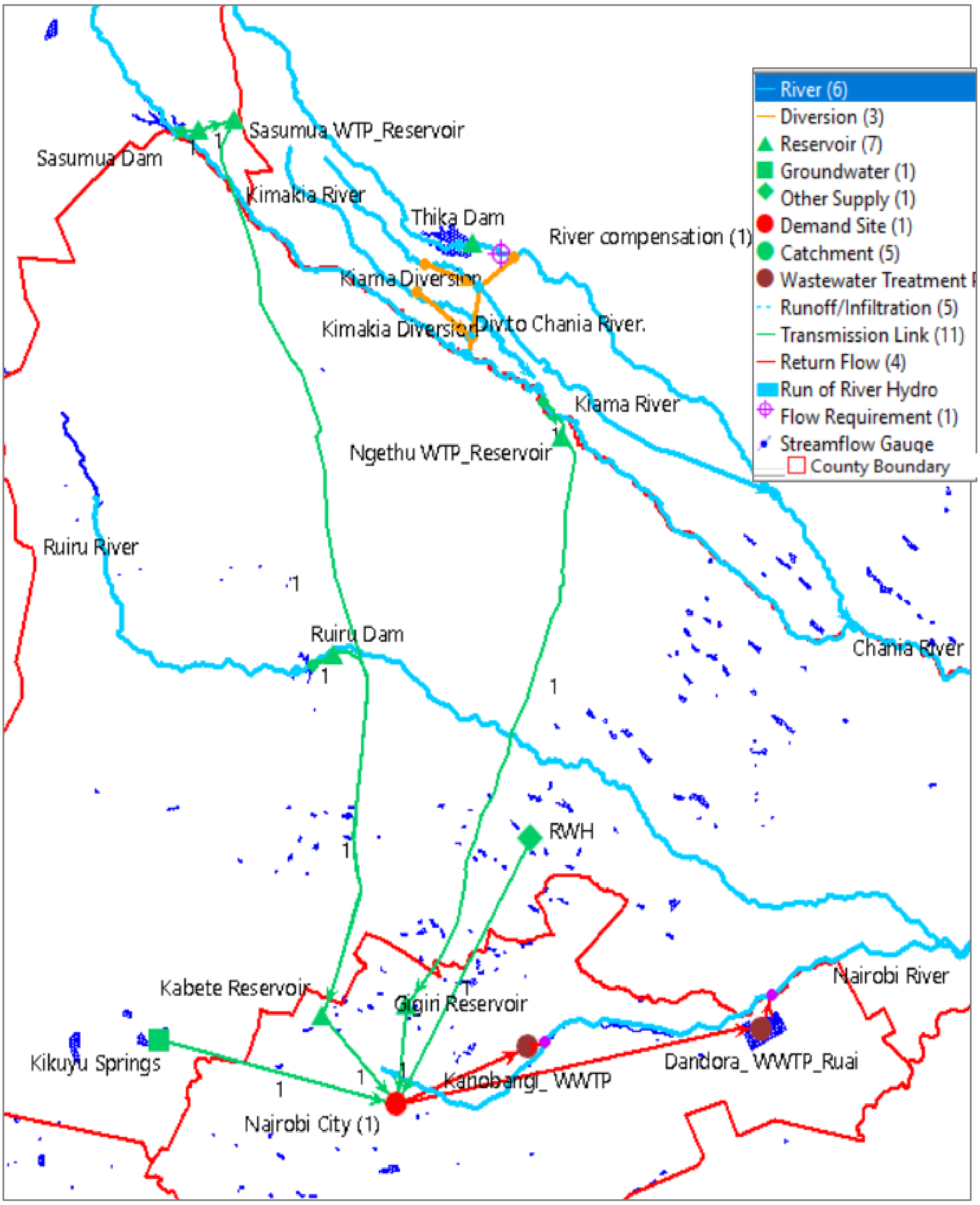


Figure 3.4: Simplified schematics for WEAP model of NCWSC.

It was important to establish the study boundary, the study period, and the research system's components as a self-contained set of data and assumptions in order to construct a WEAP model. A specific water supply system, such as a river basin, groundwater aquifer, and political or geographical boundaries, were used to define the study area (SEI, 2011).

In order to easily orient and construct and clearly understand the system situation, the spatial boundary of the study area for NCWSC was first created in WEAP using the built-in GIS-based layers (Ocean, Country, States, Cities, and Major Rivers). External raster layers (Geo TIFF or ArcView GRID files) and vector layers (ESRI Shape files) were then added. A raster layer is included in this model as the background map, and additional vector layers are added to aid in the development of the model and the presentation of the results. These vector layers include County administrative areas, NCWSC water lines, water supply sources, City areas, Land use, and Reservoirs. The WGS84, un-projected and directly based on the latitude and longitude geographic coordinate system used by WEAP must be modified using these additional vector and raster layers (SEI, 2011).

The study period for the model was established following the creation of the study area. The Current Accounts Year and Last Year of Scenarios were set for this model to be 2021 and 2040, respectively. By beginning in January and including leap days, the Time Steps per year were based on a 12-month calendar. All system information, including demand and supply data, was entered into the current accounts for the chosen current accounts year, which served as the model's base year. The current accounts data set was used to build scenarios, which were then examined for potential system changes up through the last year of scenarios.

3.3.2 WEAP data requirement and collection

The WEAP model has several data entry wizards that can be used, including Expression Builder, Time-Series Wizard, ReadFromFile Wizard, and Lookup Function Wizard (SEI, 2011). The data for demand sites and catchments, supply and resources, hydrology, critical assumptions, and other assumptions had to be input under the current accounts to reflect the current condition of the water supply-demand system. To analyse the effects of these alternatives on the future demand for water supply, the alternative data was adjusted accordingly to represent the respective future scenarios.

3.4 Collection of Data for WEAP Model

3.4.1 Population Projection

The population data of Nairobi city were obtained from the Kenya National Bureau of Statistics. The population along the transmission lines in the neighbouring counties was considered in the projection of the population that contributes to the eventual city demand for water. This population as indicated in Table 3.4 has been put as per the administrative regions of Nairobi City Water and Sewerage Company. The population figure adopted was 4,679,818 people as opposed to 4,397,073 people that are confined to Nairobi City County only. The population of the city is expected to grow at a rate of 3.8% annually.

To input the population data in WEAP, the expression builder was utilized. The Expression Builder is a “GrowthForm” function built into the WEAP model that helps project the population of the reference period (2021-2040). The expression builder can be used to construct WEAP expressions by dragging and dropping the functions and WEAP branches into an editing box. The input data in the “GrowthForm” field within WEAP for projecting the population for the reference period is the:

(i) Year of last census 2019;
(ii) Population at 2019; and
(iii) Estimated growth rates (3.8% for the reference scenario).

Table 3.4: NCWSC Area of operation population (NCWSC, 2020)

NCWSC's Region	Total Pop.Per region	Avg.Per Capita Cons (l/p/d) Per Region
Central	290,527	115
Eastern	1,120,984	101
Informal Settlement	553,032	75
North Eastern	818,001	116
Northern	1,007,809	114
Southern	212,547	186
Western	676,918	125
Total in NCWSC area of Service and Avg.Cons.	**4,679,818**	**119**

3.4.2 Water Demand

A demand site is a group of water users who share a physical distribution infrastructure or a significant source of supply for withdrawals in a specific area (SEI, 2011). This level of aggregation is frequently determined by the level of detail for water consumption data available and the level of detail desired for analysis. Demand sites for various uses of water can be merged to form aggregate demand sites, or they can be broken down into individual demand sites (SEI, 2011). Nairobi city was chosen as the study's aggregate demand site. According to NCWSC commercial directorate, the consumption of water in the demand site is divided into domestic and non–domestic water use as highlighted in Table 3.5.

(i) Domestic water use –This comprises domestic, Multi-Dwelling Units (MDU) and the water consumed through water kiosks.

(ii) Non-Domestic Water Use –Non–domestic water use is the water used for a purpose other than domestic. According to NCWSC, this category comprises of water for commercial, industrial, Institutional, and Schools.

Based on the Nairobi water billing figures (Nairobi water, 2021), boreholes were taken as 70% serving the domestic use while 30% was used for non –domestic use.

Table 3.5: NCWSC Water Consumption pattern (NCWSC, 2020)

Consumption Category	**2017/18**	**2018/19**	**2019/20**	**2020/21**
Domestic Consumption				
Domestic Billed Volume (m^3)	35,550,819	40,924,472	38,313,214	46,309,645
Multi-dwelling units billed(m^3)	24,339,075	14,703,370	18,819,568	18,148,487
Bulk consumption (m^3)	6,180,900	4,266,839	3,308,432	2,498,205
Kiosks (m^3)	2,082,661	2,509,730	2,231,682	1,931,522
Borehole Consumption (m^3)	10,706,905	15,646,748	17,729,354	14,994,186
Total	**78,860,360**	**78,051,159**	**80,402,250**	**83,882,045**
Non-Domestic Consumption				
Institutional billed(m^3)	1,654,603	1,697,140	1,737,086	1,778,904
schools billed volume(m^3)	503,721	566,885	411,046	362,517
commercial billed volume(m^3)	23,758,901	24,954,340	21,801,833	19,844,381
Industrial billed volume (m^3)	3,452,863	3,844,890	3,413,506	1,909,143
Borehole Consumption (m^3)	4,588,674	6,705,749	7,598,294	6,426,080
Total	**33,958,762**	**37,769,004**	**34,961,765**	**30,321,025**
Non-Domestic as a % of Domestic Cons	**43%**	**48%**	**43%**	**36%**

To compute the domestic demand, the 2019 population census was analysed and the per-capita consumption was established within respective areas. The water demand for the respective categories was applied using the proposed figures in the water design manual of 2005 as shown in Table 3.6.

Table 3.6: Consumption Rates (GoK, 2005)

Consumer Category	Consumption Rate (l/p/d)
Individual Connection – High Class Housing	250
Individual Connection – Medium Class Housing	150
Individual Connection – Low Class Housing	75

Non –Domestic water demand was taken as 36 % of the domestic demand based on the figures of the consumption as Table 3.5. This figure was used in the model to project the growth of of Non-Domestic demand in the future scenarios .

In the WEAP model, water demand is calculated as the product of activity level, (a measure of social and economic activity such as people or homes for cities and hectares for agricultural areas,) with water usage rate (SEI, 2011). Priority, which is expressed as an integer with 1 being the highest priority and 99 being the lowest, represents the demand site's priority for supply in relation to all other demands in the system. This user-defined demand priority system establishes the order of allocations to demand sites (SEI, 2011).

3.4.3 Catchments data

A catchment in the model is a user-defined area for hydrological activities including precipitation, evapotranspiration, runoff, irrigation, and yields on both agricultural and non-agricultural land (SEI, 2011). In order to simulate catchment processes like evapotranspiration, runoff, infiltration, and irrigation demands for a catchment, one of four methods—Irrigation Demands Only (Simplified Coefficient Method), Rainfall-Runoff (Simplified Coefficient Method), Soil Moisture Method, and MABIA Method

(FAO 56, dual Kc, Daily)—must be chosen depending on the data availability and the required level to represent the catchment processes (SEI, 2011).

In this NCWSC model, there are 5 catchments, Thika dam catchment, Kiama River catchment , Kimakia river catchment , Ruiru dam catchment, and Sasumua Dam catchment. Soil-Moisture method was used to simulate the runoff from Thika river catchment to Thika reservoir for the purposes of model calibration. For a sub-basin unit at the root zone, the Soil-Moisture method accounts for a one-dimensional, two-layer (or "bucket") soil moisture dynamic accounting system that uses empirical functions to divide water into Evapotranspiration, surface runoff, sub-surface runoff (i.e., interflow), and deep percolation.

3.4.4 Climatic data

The daily Climatic data (Rainfall, Temperature, Wind speed, and Humidity) was obtained mainly from the Thika- dam station recorded by NCWSC as shown in figure 3.5. The data on humidity had numerous gaps which were filled from the data obtained from Kenya Metrological Department (KMD) for the Thika station which is a neighbouring station. The data was analysed and an average monthly data was prepared in Comma Separated Values (CSV), then the ReadFromFile method was used to input the data in WEAP model.

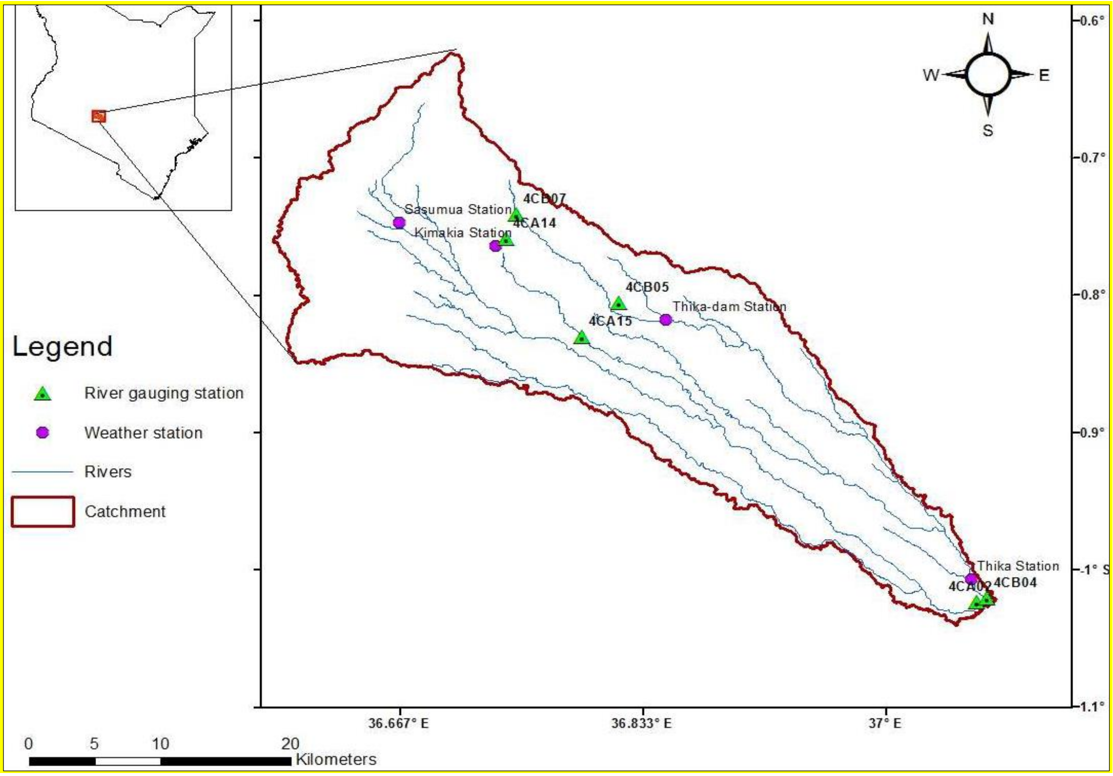


Figure 3.5: Thika-Chania catchment Weather stations (source Mutua et al 2018).

3.4.5 Land Cover data

The land use of the lower catchment (Figure 3.6) is mainly characterised by general agriculture with a predominance of coffee and maize farming, however, the upper catchment is dominated by natural forest and tea farming (Gathagu, et al, 2018). Figure 3.6 shows that the Thika river sub-catchment is mostly covered by tea and coffee as agricultural crops. FAO Irrigation and drainage paper 56, the crop coefficient Kc for Coffee and Tea range from 0.9 to 1.15. This range was adopted for the calibration of the model.

Effective precipitation is rain that does not remain on the surface of the ground or seep into the soil (Chow et al, 1988). The rate of precipitation exceeds the rate of soil infiltration during the wettest months. As a result, some of the precipitation is surface runoff into streams rather than being accessible for evaporation.

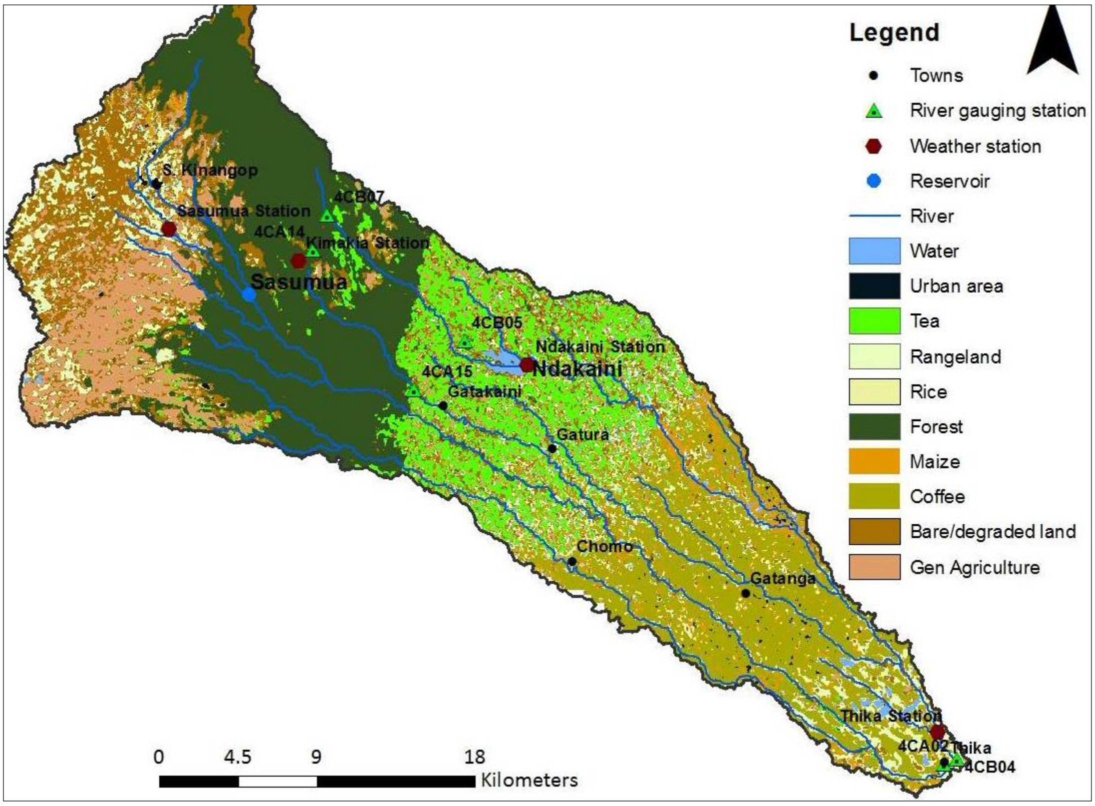


Figure 3.6: Land use at Thika-Chania catchment. (source Mutua et al., 2018)

3.4.6 Supply and Resources

The total amount of water, the amount that is readily available, and the distribution of supply sources are all determined by the supply and resources component of the WEAP model. The model then, based on the definitions of the system demand locations, catchments, as well as its hydrology, simulates monthly river flows, surface water/groundwater interactions, instream flow requirements, hydropower generation, reservoir storage, and groundwater storage (SEI, 2011). WEAP's supply and resources section includes many items like sources and links. The sources include groundwater, other supplies, and alternative water sources like desalination, rivers, and local reservoirs, which are reservoirs that are not on rivers.

Links include Runoff and Infiltration links, which connect catchments to respective runoff flow destinations, Transmission Links, which connect supply sources to demand sites and are subject to losses, physical capacity, and other constraints, and return Flows, which transmit wastewater from demand sites to wastewater treatment facilities, rivers, groundwater nodes, or other supply sources (SEI, 2011).

3.4.7 Local and Instream reservoirs

According to the user guide for WEAP 2015, the operation rules divide the reservoirs into water level-related zones as illustrated below in Figure 3.7. The water lying above the full supply level is in the Flood Control Zone and cannot be stored The Conservation Zone is the next zone, where water is used as needed to meet demand. Some limits are put in place in the Buffer Zone, the zone below, to prevent the water from being utilized rapidly (Sieber and Purkey, 2015). It is impossible to use the water in the Inactive Zone below the "dead storage level" other than to replenish reservoir losses due to evaporation and seepage (Sieber and Purkey, 2015).

Thika Dam is an instream reservoir while Ruiru and Sasumua are local reservoirs. The physical and operation data input for the three reservoirs was obtained from the respective dam stations in the three outer stations of NCWSC. The observed volume and their corresponding levels were entered into the WAEAP model by simply copying two-columns of Volume-Elevation points from excel and pasting into the Volume-Elevation table in WEAP. The monthly evaporation and observed volume data were converted to a comma Separated Value (CSV) and then input into WEAP through the ReadFromFile wizard. Thika dam was utilised for the calibration and validation of the model.

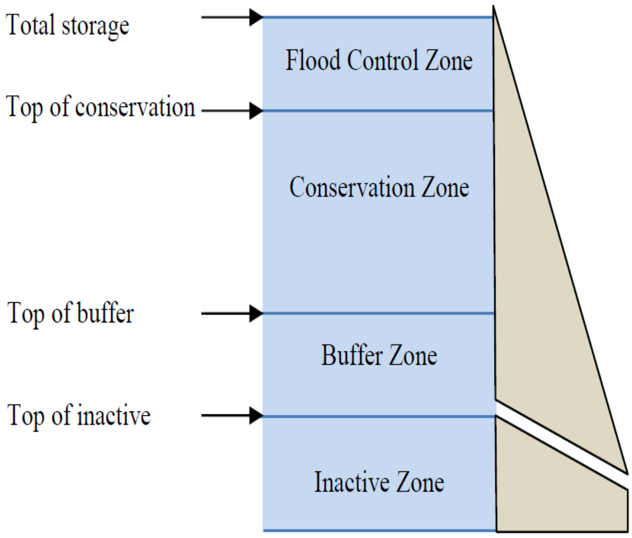


Figure 3.7: Reservoir storage zones (Source: User Guide for WEAP 2011).

3.4.8 Transmission links

Transmission links represent the movement of water from reservoirs, rivers, groundwater, and other water supplies to demand sites in order to meet the necessary demand. Additionally, they serve as a representation of the transfer of wastewater discharges from demand sites and WWTPs to additional demand sites for reuse. For water allocation, supply preferences for each transmission connection must be established (SEI, 2011). When a supply source has several demand sites, WEAP distributes water based on the demand priority and based on the supply preferences. If a demand site is connected to multiple supply sources, WEAP distributes water based on the supply preferences (SEI, 2011).

There are 11 transmission lines in this NCWSC model that connect the supply source to Nairobi City, the sole demand site, via the Kabete and Ngethu Treatment Plants. There are no constraints on any of the links, and all nodes' supply preferences are assumed to be 1, which denotes first priority, whereas reservoirs' supply preferences are assumed to be priority 99. It was assumed that the combined Non-Revenue Water (NRW) in the distribution and transmission links of surface water sources 48% .

3.4.9 Rivers

In WEAP, rivers and diversions are river nodes that are connected by river reaches, and other rivers may enter or exit a river (SEI, 2011). For the simulation of the rivers and diversions system, head flow data from the river and the maximum inflow from the diversions must be inserted. Majorly Chania river is the major source of water for Nairobi city, though there is a contribution from the Thika river and its distributaries through the Thika dam.

3.4.10 Return flow

The amount of water not consumed at the demand site is linked to the Waste Water Treatment Plants (WWTP), river or groundwater node, and other demand sites by a return flow link. In this study, 49% of the water coming out from Nairobi City is discharged into the environment while 51% is treated in WWTP, and thereafter, discharged into the Nairobi River (Nairobi Water, 2019).

3.5 Model Calibration and Validation

The main objective of model calibration is to obtain a set of parameters that apply to the watershed and accurately represent the hydrology of the catchment (parameter estimation). According to Ingol-Blanco and McKinney (2013), the model calibration procedure entails manually adjusting model parameters to reduce the discrepancy between observed and simulated results by altering the model parameter values. In this study the climatic and land use parameters were adjusted manually to fit as closely as possible; the simulated and measured reservoir volumes. The soil-moisture method embedded in WEAP involves seven soil and land use-related parameters (Sieber and Purkey 2015) that can be used to re-calibrate the hydrologic model. These are crop coefficient (Kc), soil water capacity (SWC), deep water capacity (DWC), runoff resistance factor (RRF), the conductivity of root zone (RZC), conductivity of deep zone

(DC), preferred flow direction (PFD) and initial storage fraction at the beginning of simulation of upper soil layer (Z1) and initial storage fraction at the beginning of simulation of lower soil layer (Z2). Model validation was used to assess the validity of a model to simulate the hydrologic response of catchment for conditions unlike that used during the calibration period (Legesse et al. 2003).

3.5.1 Model performance evaluation measures

The model performance was assessed using joint plots of monthly simulated and observed reservoir volumes, and statistical methods. The coefficient of determination (R^2), Nash-Sutcliffe coefficient of efficiency (NSE), standard deviation ratio (RSR) and Percent bias (PBIAS) were used to measure the goodness-of-fit of a model as below:

$$R^2 = \frac{(\sum[X_i - X_m][Y_s - Y_m])^2}{\sum((X_i - X_m)^2 \sum(Y_s - Y_m)^2)} \qquad \text{Eqn (3.1)}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - X_m)^2} \qquad \text{Eqn (3.2)}$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}(X_i - Y_i)^2}}{\sqrt{\sum_{i=1}^{n}(X_i - Y_m)^2}} \qquad \text{Eqn (3.3)}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(X_i - Y_i) * 100}{\sum_{i=1}^{n}(X_i)} \qquad \text{Eqn (3.4)}$$

Where Xi, Yi; X_m, Y_m; and n denote the ith observed monthly reservoir volume, the ith simulated monthly reservoir volume, the mean of the observed monthly reservoir, the mean of the simulated monthly reservoir volume, and the total number of observation data respectively.

3.5.2 Model sensitivity analysis

Model sensitivity analysis is the process of determining the optimal model parameters that can give reliable model values during the calibration process (Eryani et al., 2022).

In this study sensitivity analysis was performed in the Soil Moisture Method. As indicated in figure 3.8 this method performs the water balance, representing the basin in two layers of soil. In the upper (superficial) layer, the model simulates evapotranspiration, considering rainfall and irrigation in agricultural and non-agricultural lands, surface and subsurface flow, and changes in soil moisture. This allows the characterization of land use, soil type, and its impacts on these processes. In the lower layer, simulations are performed for the river runoff routines and changes in soil moisture. The great difficulty in using the method lies in the need for greater parameterization of the soil and climate (Silva et al., 2017).

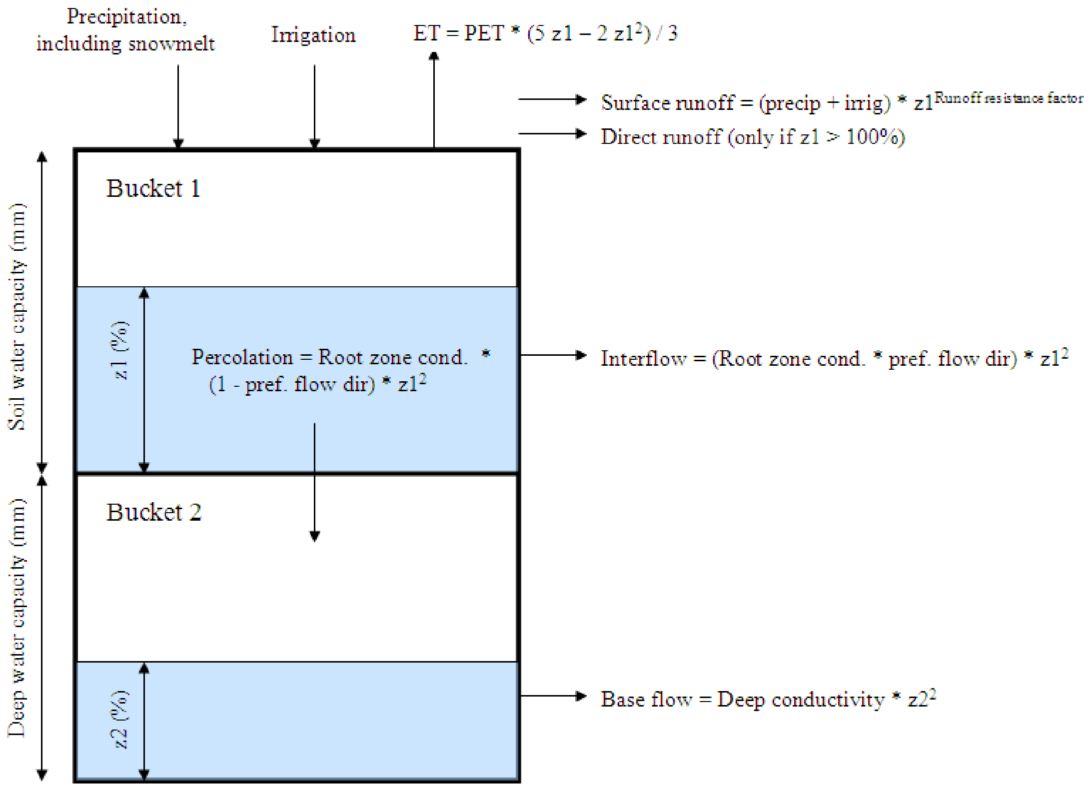


Figure 3.8: The Two-bucket model (SEI,2011)

A watershed unit can be divided into N fractional areas representing different land uses/soil types, and a water balance is computed for each fractional area, j of N. Climate is assumed to be uniform over each sub-catchment (SEI,2011). Thika River catchment water balance is given as per the equation (Eqn 3.5).

$$SWC_j \frac{dz_{1,j}}{dt} = Pe(t) - PET(T)K_{c,j}(t)\left(\frac{5z_{1,j}-2z_{1,j}^2}{3}\right) - Pe(t)\, z_{1,j}^{2\frac{RRF_J}{2}} - PFD_jRZC_Jz_{1,j}^2 - \left(PFD_j\right)RZC_1z_{1,j}^2 \text{ ...Eqn (3.5)}$$

where, $Z_{1,\,j}$ is the relative storage given as a fraction of the total effective storage in the root zone, and SWC_j represents the effective total storage of the top layer (mm). The first term of equation 3.5 is defined as precipitation. The second term is the potential evapotranspiration of the reference crop (Penman-Montieth) in mm day-1, and $K_{c,j}$ is the crop/plant coefficient for each percentage of soil cover. It refers to the evapotranspiration of each fraction of the area. Surface runoff is represented by the third term, where P_e is effective precipitation and RRF (Runoff Resistance Factor) is a flow resistance factor. Lower values of RRF_j relate to a particular class of soil cover that will encourage a stronger response to surface run-off.

The subsurface flow and percolation are represented by the fourth and fifth terms of equation 3.5, respectively, where the RZC_j (Root Zone Conductivity) parameter is an estimate of the conductivity of the upper storage layer (mm h^{-1}) and PFD_j (Preferred Flow Direction) is an adjustment parameter related to soil, topography, soil cover type.

The mass balance for the second layer ($z_{2,\,j}$) is obtained according to Equation 3.6.

$$DWC_j \frac{dz_{2,j}}{dt} = \left(1 - PFD_J\right)RZC_Jz_{1,j}^2 - DCz_{2,j}^2 \qquad \text{Eqn (3.6)}$$

Where deep percolation from the upper storage into the bottom layer is, obtained in equation 3.5, DC (Deep Conductivity) is the conductivity of the lower layer (mm h^{-1}), represented as a single value for each Sub-basin and DWC_j (Deep Water Capacity) is the storage capacity of water in the bottom layer (mm).

The sensitivity analysis of the WEAP model was performed manually, varying each input parameter individually, while the others were kept constant. Silva et al. (2009) presented a Relative Sensitivity Index (SI), according to Equation.3.7.

$$IS = \frac{\frac{O_1 - O_2}{O_{12}}}{\frac{I_1 - I_2}{I_{12}}} \qquad \text{Eqn (3.7)}$$

Where IS is the sensitivity index of the model to the input parameters; O_1 is the result obtained by the model in response to the lowest input value used in the sensitivity analysis, and O_2 is the result obtained by the models in response to the highest input value used in the sensitivity analysis, O_{12} is the mean of the results obtained with the highest and lower input value; I_1 is the smallest input value, I_2 is the largest input value; and finally, I_{12}, the mean values of the input values.

The parameters used in the sensitivity analysis of the WEAP model were SWC Soil Water Capacity (SWC), Deep Water Capacity (DWC), Root Conductivity (RZC), Runoff Resistance Factor (RRF), Preferred Flow Direction PFD). The variation of the parameters was - 30%, -20%, -10%, 10%, 20%, and 30%, and the standard was based on the parameters of the calibrated model. The values of the calibrated parameters used as standard can be seen in Table 3.7.

The perturbation that the variation of the parameters promoted in the results simulated monthly volumes by the model in relation to the observed Thika dam volumes was checked coefficient of efficiency Nash-Sutcliffe (NSE).

Table 3.7: Calibrated parameters of the WEAP model for the Thika River Catchment

Parameter	
Soil Water Capacity (SWC)	600 (mm)
Deep Water Capacity (DWC)	800 (mm)
Deep Conductivity (DC)	20 (mm/s)
Root Zone Conductivity (RZC)	20 (mm/s)
Runoff Resistance Factor (RRF)	2
Preferred Flow Direction (PFD)	0.5

For the WEAP sensitivity analysis, the calibrated model was used, for the period 1997 to 2016 of the observed reservoir volumes.

3.6 Reference Scenario

The current accounts are used to create the reference scenario, also referred to as the "business as usual" scenario, which represents the fundamental definition of the current system and specifies supply and demand data for the first year of the study on a monthly basis (SEI, 2011). The reference scenario preserves the current data for the whole time horizon with no significant modifications and serves as a benchmark for the other scenarios that represent the changes in the status–quo.

In this study, the reference scenario is the scenario in which the current account year 2021 is extended to the 'future' (2022-2040). Reference Scenario was applied to analyse the situation of NCWSC without any development in of the system except the population growth with normal growth rate of 3.8%. Non-Revenue Water of 48% spread all through the prediction period. The actual water demand as determined from the NCWSC actual consumption rate and the water design Manual of 2005 was used during the setting up of the model in the current and used in the projection of the reference scenario.

3.7 Creation of Scenarios

Other future scenarios were analysed to understand their impact on the Nairobi city water system as shown in figure 3.9. The following future scenarios were developed and analysed in this study to understand the impact of external changes and management practices on both the demand and supply sides of the water system.

i. Reduction of Non-Revenue Water (NRW)

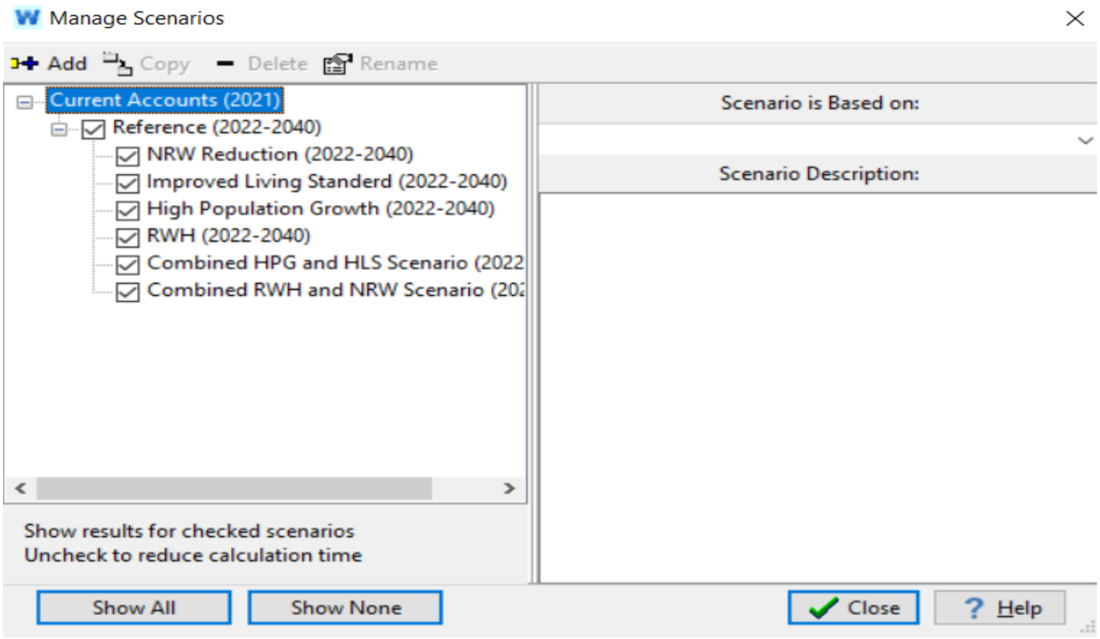
ii. High Population Growth (HPG) scenario: It analyses the situation with a high population growth rate of 4.2% adopted for this research.

iii. Higher Living Standards (HSL) scenario: It analyses the situation of increase in water consumption rate from the present of rate 43 m^3/day to 57 m^3/day as per the water design manual of 2005 by 2040 because of higher living standards.

iv. Introduction of Rain Water Harvesting as an alternative water supply to supplement the existing water supply system

v. Combining of the High Population Growth and High Living Standard

vi. Combining the Rain Water Harvesting and Non-Revenue Water management



Current Accounts (2021)
  ☑ Reference (2022-2040)
    ☑ NRW Reduction (2022-2040)
    ☑ Improved Living Standerd (2022-2040)
    ☑ High Population Growth (2022-2040)
    ☑ RWH (2022-2040)
    ☑ Combined HPG and HLS Scenario (2022
    ☑ Combined RWH and NRW Scenario (20

Show results for checked scenarios
Uncheck to reduce calculation time

Figure 3.9: Scenarios in WEAP model

3.7.1 Reduction of Non-Revenue Water (NRW)

According to the strategic plan of Nairobi City Water and Sewerage Company, there is an elaborate plan to reduce the Non-Revenue Water (NRW) from 36% to 25% by 2024. However, the figures reviewed by the water services regulatory board put the NRW for NCWSC at 48%. Thus in this study, on the Scenario for reduction of NRW, the same rate proposed by NCWSC for NRW reduction was adopted. The figure was projected to reduce from 48% to 28% by 2040. This data was input into the WEAP model under the demand side in the scenario for NRW reduction in the module for loss and reuse, then a “growthfrom” function was used to negatively grow the NRW by -2.8% from 2021 to 2040.

3.7.2 High Population Growth (HPG) scenario

This scenario examines the effects of Nairobi City's population growth rate rising from its typical rate of 3.8% to 4.2% as a result of urbanization, industrialisation, and rural-to-urban migration. In this case, the Annual Population Growth Rate in Key Assumption is entered as 4.2%, and using this input data and the "growthfrom" function, the Annual Activity Level of Nairobi City is determined.

3.7.3 Higher Living Standards (HSL) scenario

This scenario explores the impacts of rising water consumption rates in line with increased living standards caused by Nairobi City's economic development. The water consumption rate for Nairobi City in this scenario was based on the Kenya design manual for water and sanitation 2005. The consumption of the informal settlement region area was taken as low living and a figure of 75 l/p/d was adopted while in the formal regions, the figure ranged from 75l/p/d through 150l/p/d to 250l/p/d. From the demand analysis, the Southern administrative region had the highest per capita demand at 186 l/p/d while the Eastern was the least per capita demand at 101 l/p/d. This is attributed to the factor that the Eastern region hosts the most semi-informal settlement. An average of 119 l/p/d was used in the reference scenario translating to 43m^3/person per year.

In the improved living standard, it was assumed that all the 75l/p/d was upgraded to 150l/p/d while maintaining the 250 l/p/d for the high living standard. In this Scenario, it was assumed that the per capita water consumption was to improve from 43m^3/per person per year in the reference scenario to an average of 56.9 m^3/person/ year in the HLS scenario . The figure was directly entered into the WEAP model under the water use rate.

3.7.4 Rain Water Harvesting (RWH) scenario.

Urban stream degradation, flooding, and the current water crisis issues might all be resolved by using RWH in urban areas (Fletcher et al., 2008). Nairobi is already a built-up city, making it nearly difficult to use the RWH approach in existing structures, however, RWH facilities may be included in new buildings. Therefore, the county government should encourage practicing this technique in new buildings not only for demand control but also for city flood control option.

Aung, 2014 assumed one squared metre rain water harvested area for each increased person after the Current Accounts year. Kooke et al. (2012) used an average roof area of 100m^2 corresponding to a household of 5 people. This implies that 20m^2 will represent one person, while Aladenola and Adeboye (2010) used an average roof area per dwelling in Abeokuta as 80 m^2 per household and a household was taken to consist of 5 persons representing 16 m^2 of roof area per person. In this study, a roof area of 50m^2 was used per household and one household was assumed to be comprised of 3 persons (KNBS, 2020). Therefore, to get the roof area it was assumed that every increased person from the current year will have a corresponding roof area of 17 m^2.

The amount of rainwater (RWH) harvested in urban areas was easily determined by using the formula in the Kenya water design manual of 2005, (GoK, 2005). According to the manual, to compute the rainwater harvested per household, the yearly rainfall with a 90% chance of occurring should be considered reliable. The yearly rainfall with a 90% likelihood for Nairobi was picked from the probability maps in Appendix B of the Kenya water design manual of 2005 to estimate the available rainfall.

For a catchment of area, A m^2 receiving rainfall (R) in a month, the yield Y is calculated as follows: -

$$Y = \frac{fxAxR}{1000} \text{ m}^3\text{/Year}$$

Where;

A =Area computed from increased population

f=Run-off coefficient which was taken as 80%

R=Monthly rainfall. From the probability maps, Nairobi has a yearly rainfall range of 750-1000 mm. In this study, an average yearly rainfall of 750mm was adopted.

In the WEAP model for NCWSC, firstly, the RWH supply is created and connected the Nairobi City with transmission links via virtual RWH reservoirs. This virtual RWH supply source and RWH reservoir represent the RWH facilities of the newly constructed buildings in Nairobi City from the current year of 2021. Precipitation data of Nairobi City, harvested area, calculated by multiplying 17 m^2 per capita rate with increased population in Nairobi City after 2021.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

In order to comprehend the water situation in the city, this chapter explains the current situation in Nairobi. The evaluation of the simulated results in the reference scenario was utilized to determine whether the WEAP model was appropriate for capturing the current situation. The results of the reference scenario and the other scenarios was then compared and contrasted in order to assess the positive and negative effects of the various scenarios.

The results presented in this chapter focuses mainly on the water demand coverage and unmet demand of Nairobi City in the Reference Scenario (the Current Accounts) and the impacts of other alternative scenarios on unmet demand and demand coverage.

4.2 Model Calibration and Validation

The model performance was evaluated by comparing the observed volume data from the Thika dam from 1997 to 2016 with the run-off generated by the Thika river catchment using the Soil-Moisture method embedded in the water evaluation and planning model. The land use and climatic data such as crop coefficient, precipitation, average monthly temperature, relative humidity, and wind speed parameters were used as the input data to the Soil-Moisture method to simulate the runoff. The model was calibrated to parameters using the manual (trial-and-error) method until a good fit was observed between the measured and simulated reservoir volume. The data from the year 1997 to 2008 was used for calibration while from 2009 to 2016 the observed volume data was used for validation. The monthly joint graphs of observed and simulated volumes showed a good agreement between the simulated and the observed volumes both for calibration and validation. Fig 4.1a shows that there was a reasonable agreement between the measured and simulated reservoir volumes during the calibration period with R^2, NSE, RSR, and PBIAS of 0.70, 0.98, 0.13, and 4.9 respectively. Fig.4.1b shows the scatter plot of the observed and simulated data, the results present a good fit of correlation with R^2 of 70%.

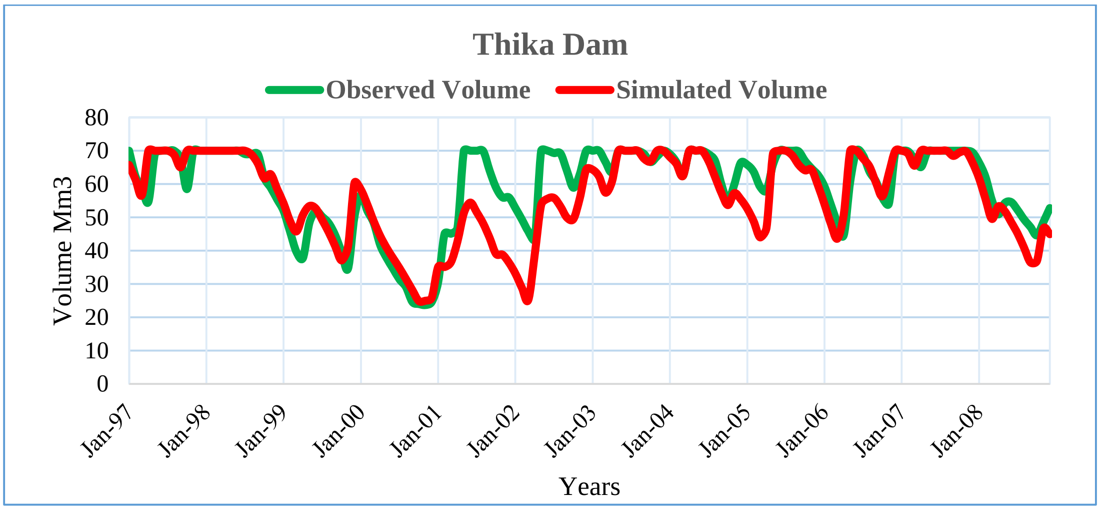


Figure 4.1a: Thika dam monthly volume Calibration results

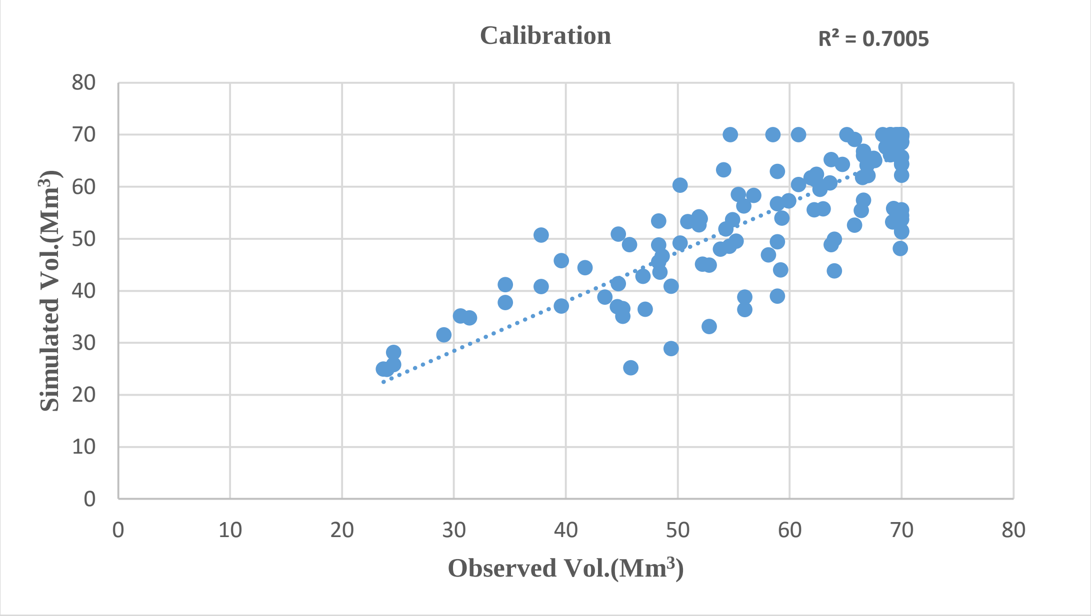


Figure 4.1b: Scatterplot of the observed and simulated Thika Reservoir Volumes-calibration results.

For the model validation, the mean monthly observed and simulated reservoir volumes shown in Fig. 4.2a exhibited a strong agreement with R^2, NSE, RSR, and PBIA of 0.74, 0.98, 0.15, and 9.1 respectively for the Validation period. The scatter plot for the validation results shows an R^2 of 74%. (fig.4.2b).

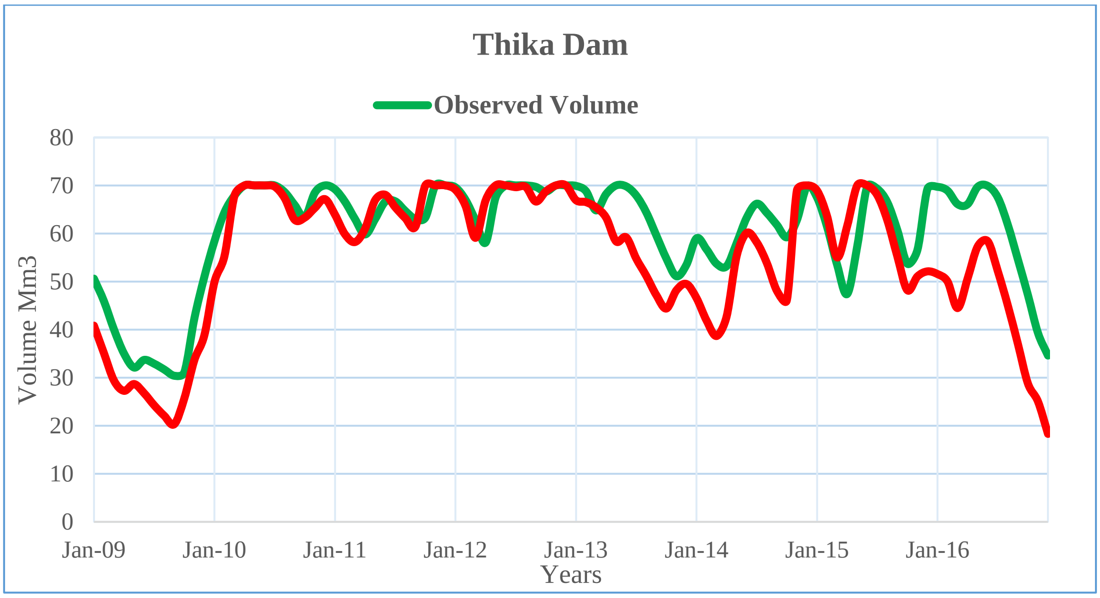


Figure 4.2a: Thika dam monthly volume validation results

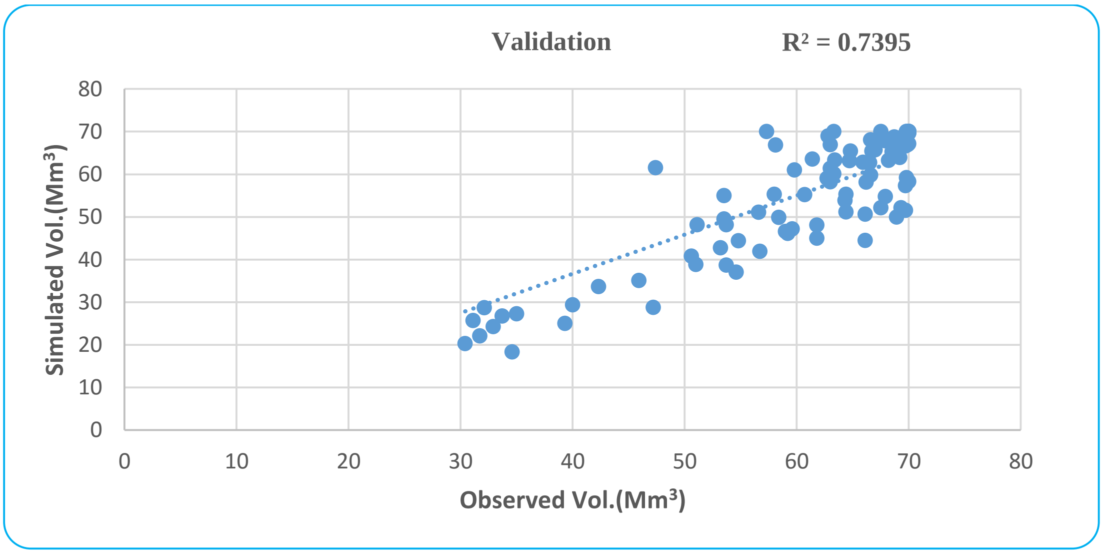


Figure 4.2b: scatterplot of the observed and simulated Thika Reservoir Volumes-Validation Results

4.2.1 Model performance evaluation measures

The effectiveness of the model performance was evaluated using the statistical parameters from the observed and simulated reservoir volume data. Higher values of the coefficient of determination (R^2) indicate reduced error variation, with values larger than 0.5 typically considered acceptable (Santhi, et al. 2001). Nash-Sutcliffe Efficiency (NSE) ranges between $-\infty$ and 1.0, with NSE = 1 being the ideal value (Moriasi et al. 2007). NSE values of 0.75 to 1.0 and RSR values that range from 0.0 to 0.5 are taken as excellent model performance while NSE of 0.65 to 0.75 and RSR of 0.5 to 0.6 are taken as good model performance. The model is taken to be performing averagely with NSE of 0.50 to 0.65 and RSR of 0.6 to 0.7. When the statistical parameter of NSE and RSR is less than 0.5 and more than 0.5 respectively, then the model is deemed unsatisfactory for monthly data (Moriasi et al. 2007). According to Gupta et al., (1999), the ideal value of PBIAS is 0.0, with low values indicating perfect model simulation. Positive values indicate an underestimating bias in the model, whereas negative values indicate an overestimation bias in the model. PBIAS of 25 is generally thought to be good (Moriasi, et al 2007). The model performed very well during calibration and attained R^2, NSE, RSR, and PBIAS values of 0.70, 0.98, 0.5, and 2.0, respectively. These results, demonstrate significant consistency between the monthly observed and simulated reservoir volume (Moriasi et al., 2007). The statistical parameters for model validation demonstrated a very high degree of agreement between the observed and simulated reservoir volumes, with R^2, NSE, RSR, and PBIAS values of 0.74, 0.98, 0.15, and 9.1 respectively. The statistical evaluation parameters are summarized in Table 4.1.

Table 4.1 Model statistical performance parameters for measured and simulated reservoir volume Thika dam

Evaluation Statistics				
	R2	**NSE**	**RSR**	**PBIAS**
Optimal value	1.00	1.00	0.00	0.00
Calibration	0.70	0.98	0.13	4.90
Validation	0.74	0.98	0.15	9.10

WEAP hydrological model is able to replicate catchment hydrology processes. Asghar et al. (2019) used a Water Evaluation And Planning (WEAP) model to simulate streamflow in the central Indus Basin and found that it was able to achieve NSE and R^2 values of 0.85 and 0.86, respectively. Abera & Ayenew (2021) assessed the capacity of the WEAP model to predict sub-basin hydrology in the Central Rift Valley basin, Ethiopia. The model achieved R^2, NSE, and RSR of 0.99, 0.97, and 0.15, respectively. Using the WEAP model, Ingol-Blanco and McKinney (2013) evaluated the hydrologic processes in the Rio Conchos Basin. With values of NSE=0.65-0.87 and R^2 =0.92-0.97, the model performed well.

4.2.2 Sensitivity analysis

Figure 4.3 shows the monthly water volumes observed and estimated by the WEAP model for the Thika river catchment for the years 1997 to 2016, and the adjustment by the Nash and Sutcliffe Coefficient for this situation was 0.81, which is classified as good.

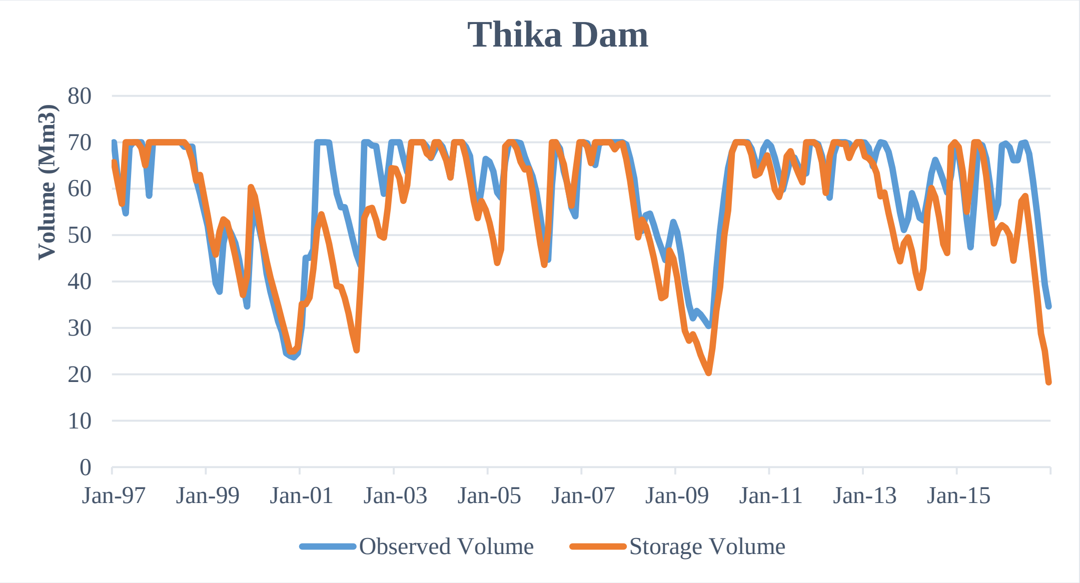


Figure 4.3: Observed and estimated monthly volumes for Thika river catchment

After the adjustment of the soil parameters in the WEAP model for the Thika river catchment, table 4.2 presents the Sensitivity Index results.

Table 4.2: Sensitivity analysis of the WEAP model for Thika River Catchment

Parameters	I_1	I_2	O_1	O_2	IS(%)	Ranking
SWC	350	455	0.79	0.77	-0.042	3
DWC	560	1040	0.81	0.81	-0.014	5
RRF	1.4	2.6	0.78	0.71	-0.175	1
RZC	14	26	0.79	0.83	-0.052	2
DC	14	26	0.80	0.80	0.004	6
PFD	35%	65%	0.80	0.81	0.017	4

The results show that RRF has the biggest impact on the water volumes estimated by the WEAP model, followed by the RZC, SWC, PFD, and then DWC while the DC or the conductivity in the lower layer has a negligible impact on the model sensitivity.

From the Sensitivity results, it was established that the lower the sensitivity index value for RRF, the higher the simulated volume would be. This, therefore, means attention should be given to this parameter during the calibration process of the WEAP model.

Large RRF values significantly change the simulation volume proportionately. Conversely, low RRF values have corresponding low simulated volumes. Having very large or very small values of RRF can still present results that contradict the expected behaviour.

The second factor to have a higher sensitivity to the WEAP model was RZC or hydraulic conductivity in the root zone, however, unlike the SWC and RRF, this parameter showed a directly proportional relation to the output values of the model. The RZC value significantly affects the interflow and percolation, thus large RZC value results in a low flow rate, correspondingly the simulated reservoir volume will be less and vice versa.

The third parameter that presented the highest sensitivity to the model was the SWC, also presenting an inverse relation, that is, as the SWC value increases, the lower the output value of the model. With large SWC values it assumed that a lot of water is accommodated and small values of SWC shows that a lot of water flows directly.

The PFD was the fourth parameter in the sensitivity ranking, however, its value was very low when compared to the RRF, SWC and RZC, which makes it little influential in the model response. This can also be observed in the DWC parameter or water storage capacity in the lower layer. The DC parameter was insignificantly sensitive in relation to the data simulated by the model. Figure 4.4 shows the deformation of the NSE as a result of the changes of the model parameters.

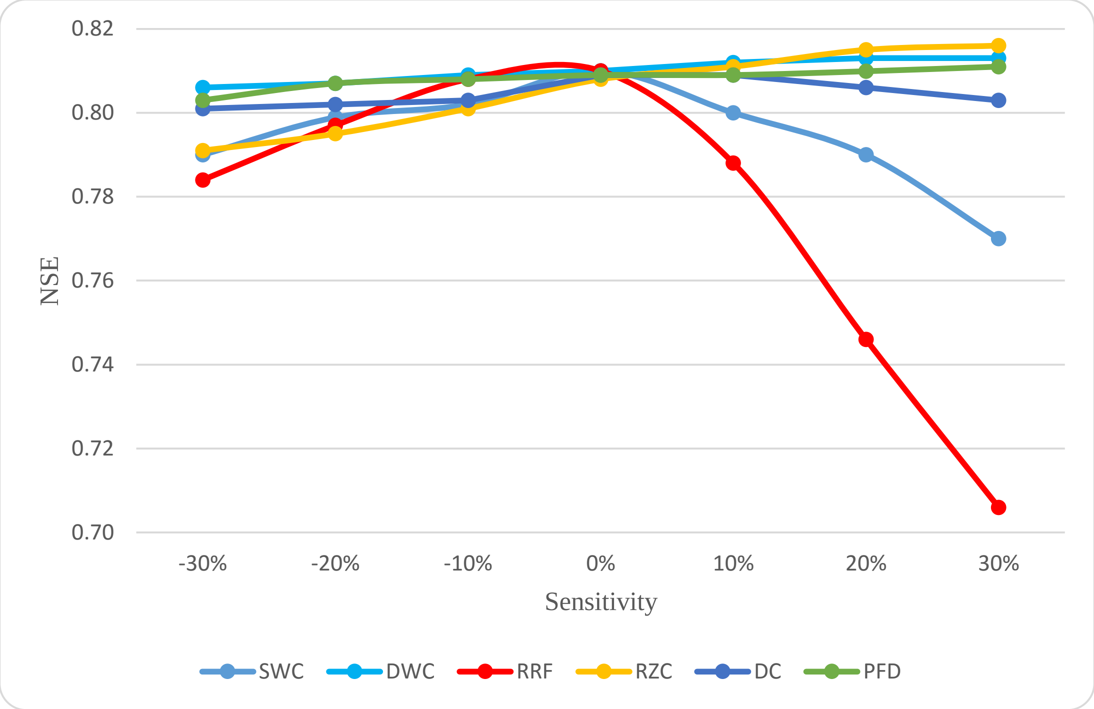


Figure 4.4: Deformation in Nash-Sutcliffe Efficiency as a function of parameter variation.

Although RZC is the second parameter with high sensitivity to the model, the variations on this parameter didn't promote drastic changes in the Nash-Sutcliffe coefficient, as compared to the SWC which comes third in the ranking.

4.3 Reference Scenario

The Reference scenario is the case where the Current Account Year of 2021 is extended to the 'Future' as an extension of the Current Situation (2022-2040). In this scenario, there are no significant adjustments made (SEI 2011). Using data from the Kenya Bureau of Statistics, it was assumed that the population would grow linearly (KNBS, 2020). The non-revenue water (NRW) rate for the water utility is assumed to remain constant at 48% during the forecasting period. It is anticipated that the current water supply won't change over time. Given the restrictions imposed by the model's simplification and the data constraints, the model accurately predicts reality for the years 2022 to 2040.

4.3.1 Population Projection

The WEAP model was used to project the population of Nairobi city for the reference years (2022-2040). The built-in "GrowthFrom" function in WEAP was used to project the population in the future by assuming a high growth rate of 4.2% instead of 3.8% in the reference scenario . The anticipated populations for the reference and high population growth scenarios are shown in Table 4.3.

Table 4.3: Population projection for Reference and High Population Growth (HPG) scenarios-WEAP model results.

	2021	**2025**	**2030**	**2035**	**2040**
Reference Scenario (3.8%)	5,042,242	5,853,466	7,053,422	8,499,368	10,241,732
High Pop. Growth (4.2%)	5,042,242	5,944,216	7,301,854	8,969,572	11,018,192

From table 4.3 it can be seen that if the population growth rate can increase by as little as 0.4% from the current population growth rate 3.8%, the overall population will have increased by more than 1.1million people in reference to the “business as usual” scenario. It is expected that the population will reach 10.2 million people by the year 2040, if the current trend of population growth rate is maintained. From figure 4.5, the gap in population growth continues to widen at a faster rate as you approach the year 2040.

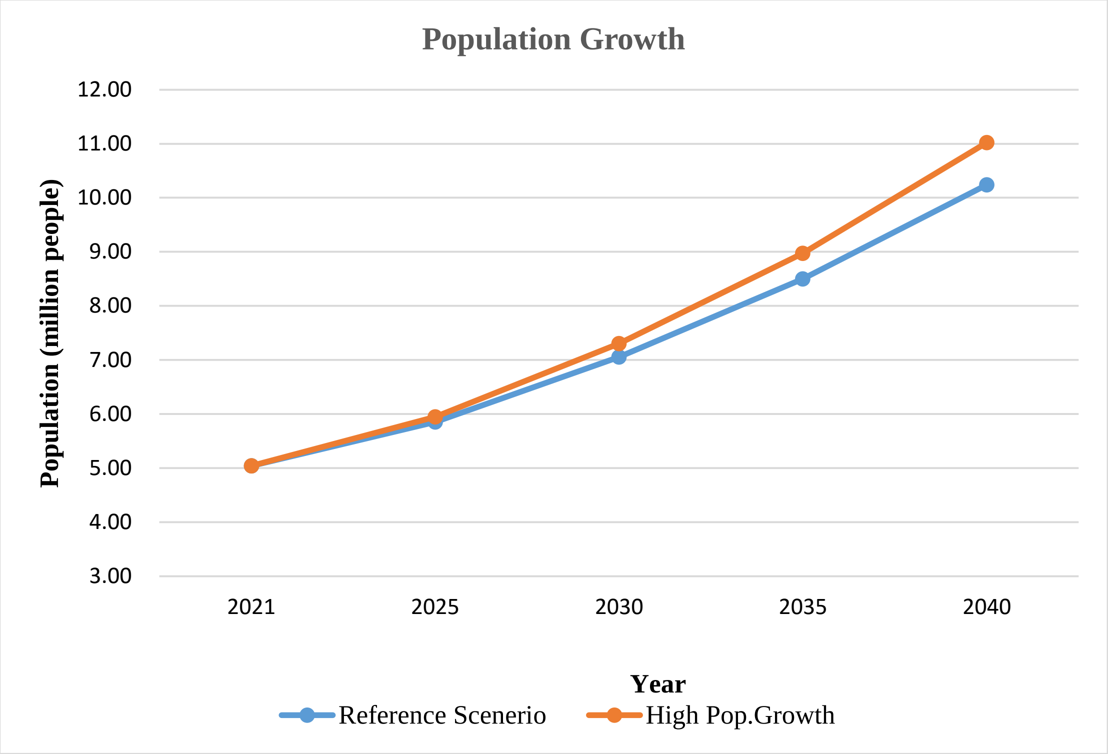


Figure 4.5: Projected population growth in HPG and "Business as usual" Scenario

4.3.2 Estimation of Future Demand for Nairobi City

Figure 4.6 shows the simulation results for the reference scenario for Nairobi City's water demand. This scenario predicts a steady increase in the City's water consumption from 298 Mm^3 per year in 2021 to 605 Mm^3 per year in 2040. It is clear that the city's anticipated demand would more than quadruple that of the current year.

The water demands are calculated by considering the factor of domestic water consumption and population growth in the region. In the base year the population growth was based on the census report (KNBS, 2019) estimated for Nairobi city. This figure was applied as the population growth for the entire modelling period.

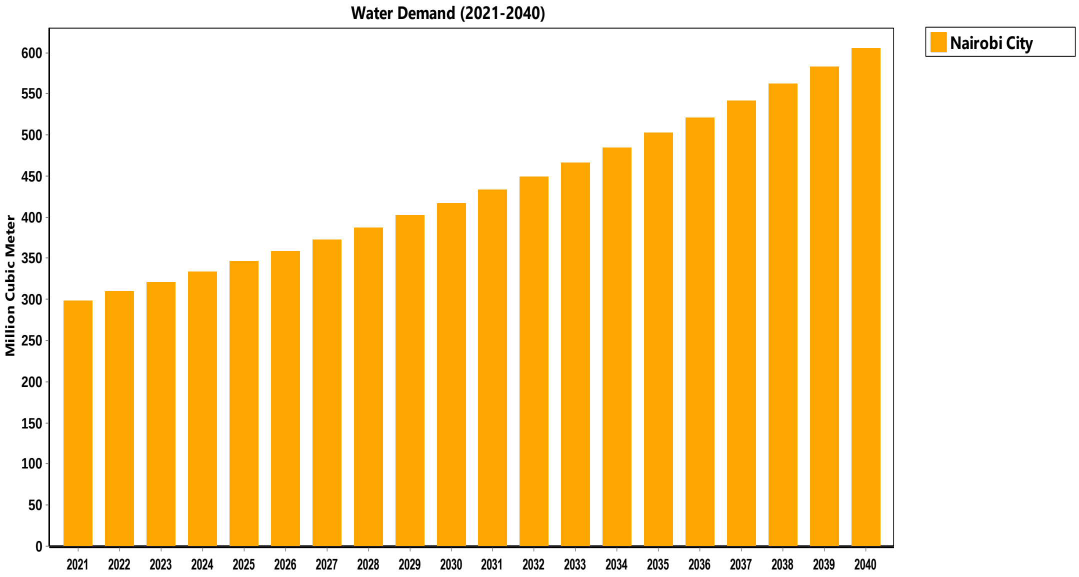


Figure 4.6: Projected water demand under the reference scenario

The domestic demand carries the largest share of the water demand of the city. As shown in table 4.4. The domestic demand is projected to be 445 Mm3 against 160 Mm3 of the Non –domestic demand in the same year

Table 4.4: Domestic and Non-Domestic water demand under reference Scenario.

	2021	**2025**	**2030**	**2035**	**2040**
Domestic Consumption	219,009,774	254,245,287	306,365,373	369,170,037	444,849,609
Non Domestic Consumption	78,843,519	91,528,303	110,291,534	132,901,213	160,145,859
Total Demand	**297,853,292**	**345,773,590**	**416,656,908**	**502,071,251**	**604,995,468**

4.3.3 Water supply requirement and Unmet Demand for Nairobi City

In the reference Scenario, the result for the supply delivered amount in Nairobi city is a maximum of 215M m^3/year in the current account all through to the modelling period. The water supply requirement is increased by the fact that there is a Non-Revenue Water of 48%. This raises the water requirement from 573 Mm^3 in 2021 to 1,163 Mm^3 in 2040 as shown in figure 4.7.

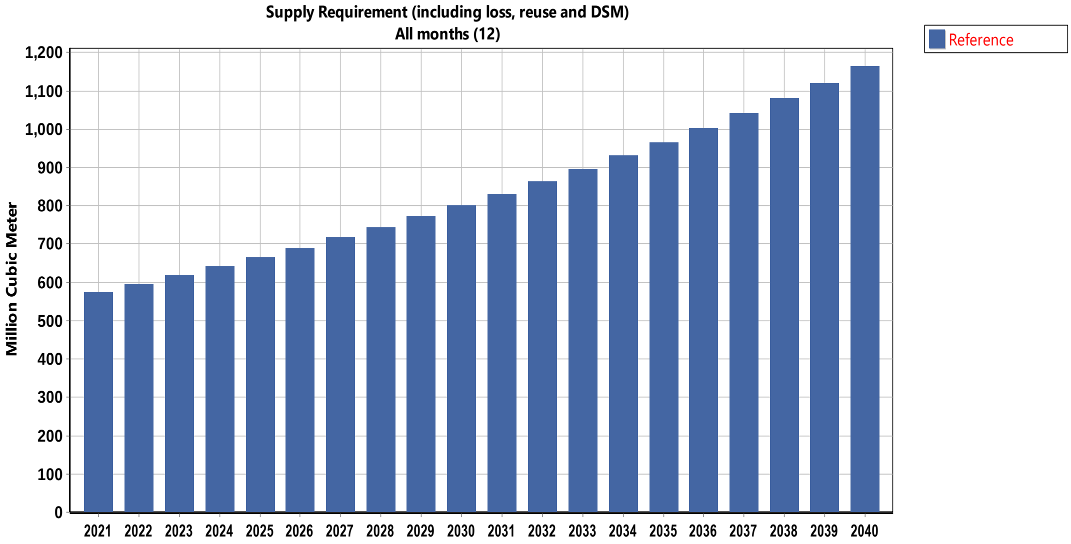


Figure 4. 1: Supply Requirement under the reference Scenario

The unmet water demand increases from 358 Mm^3 to 948Mm^3 respectively in the reference scenario (Table 4.5). As opposed to the water demand, unmet water demand is affected by the NRW figure. The more NRW increases the greater the figure for the unmet water demand. The demand coverage in the reference scenario decreases progressively from 37% coverage in 2020 to 19% in 2040.

Table 4.5: Unmet Water demand and demand coverage under reference Scenario.

	Reference Scenario Unmet water demand (m^3)				
	2021	2025	2030	2035	2040
Unmet Water Demand	357,754,793	449,909,211	586,223,284	750,478,043	947,826,823
Demand Coverage	37%	32%	27%	22%	19%

4.4 Other Scenarios

4.4.1 Reduction of Non -Revenue Water

This scenario analysed a situation with establishment of NRW control management plan. According to NCWSC strategic plan 2019/2020-2023/2024 (Nairobi water 2019), the company has proposed to reduce Non-Revenue Water (NRW) from the current 36%

to 25% in the year 2025. However, the data presented to Water Services Regulatory Board (WASREB) for the year 2020/2021 for NRW was 48%. The reduction of NRW was taken into account during the modelling and if the company will maintain the same proposed pace of NRW reduction it is likely to have a NRW of 28% by the year 2040. To decrease the NRW amount from 48% current year to 28% in the year 2040, a yearly reduction of -2.8% on the existing NRW was adopted. This was then input in the model as a negative growth from the Current Accounts. Increase in NRW does not correspond to increase in the water demand, but it increases the water supply requirements and by extension increases the unmet water demand.

The results indicate that reduction of NRW in the system has the highest impact on the unmet water demand. From the analysis, the unmet water demand of the city can reduce from 948Mm^3 to 624 Mm^3 in the year 2040 (Figure 4.8).

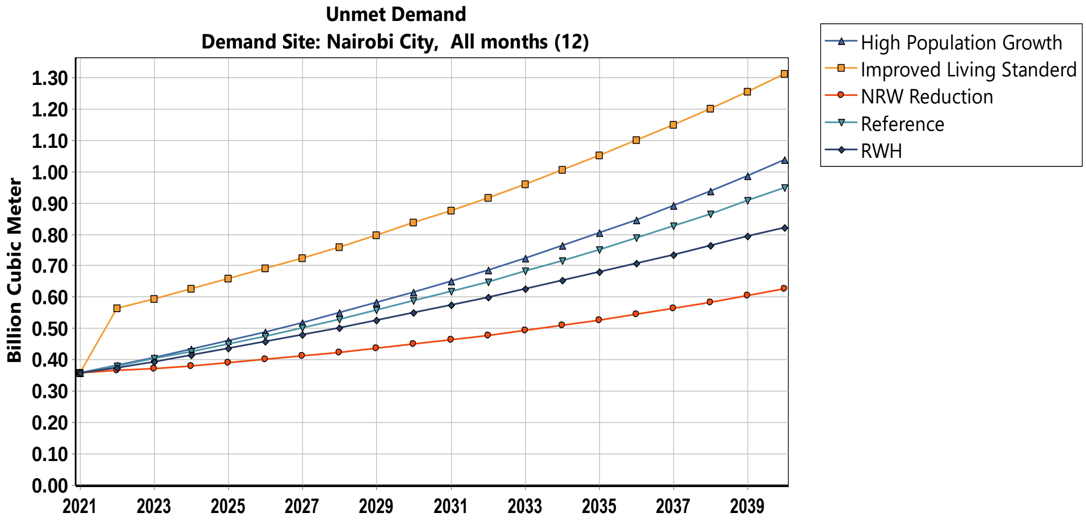


Figure 4.8: Unmet Water Demand under the NRW reduction in Comparison to others

However, the demand coverage of this scenario is much less as compared to the RWH scenario. With NRW scenario having 26% coverage as compared to RWH which has 29% coverage by 2040 (Table 4.6)

Table 4.6: Water demand coverage under the NRW Scenario.

	2021	2025	2030	2035	2040
NRW Reduction (%)	37	35	32	29	26
Reference (%)	37	32	27	22	19
RWH (%)	37	35	31	30	29

NRW has no impact on the water demand of the city, however it has a considerable impact on the water requirement of the city to meet the demand. In this scenario a reducing figure of the NRW was considered as compared to the constant NRW used in the reference scenario. The results show that by reducing NRW, the trend for supply requirement goes considerably down from 1,163 Mm^3 to 840 Mm^3 in the year 2040 (Figure 4.9).

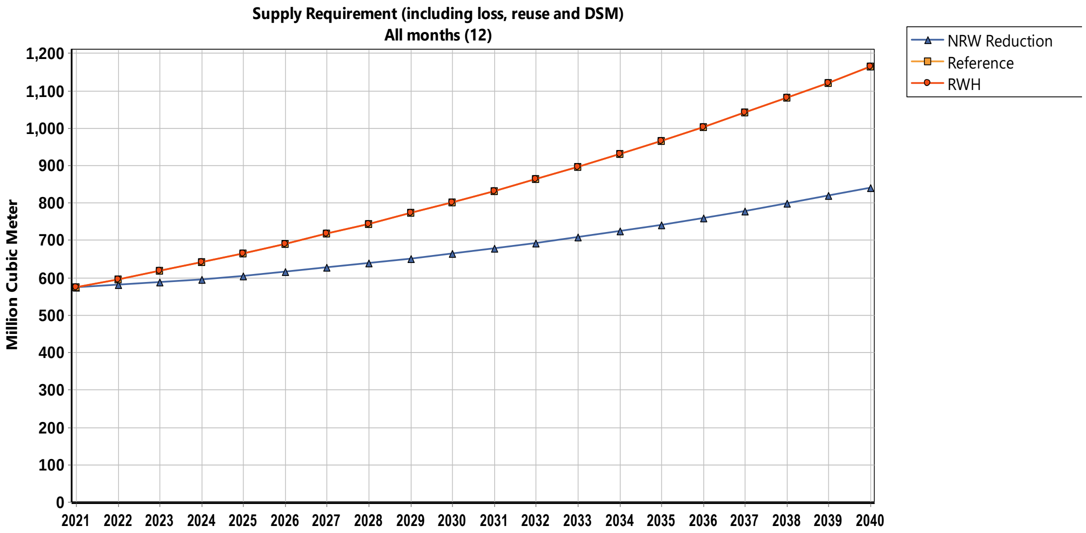


Figure 4.9: Water Supply requirement under the NRW reduction Scenario

4.4.2 Higher Living Standards (HLS) scenario

The daily water demand adopted in this research was 119 l/p/d derived from the Census report and the water demands bands as per the water design manual of 2005 (GoK, 2005). Nairobi city water and Sewage Company, has categorized the water demand into two; domestic and non-domestic. Non-domestic water demand used was based on

36% of the overall domestic water consumption. In this scenario, it was assumed that when living standards improve, the per capita water consumption will also rise correspondingly. Thus all the demands in the category of Low-Class Housing (LCH) were upgraded to Medium Class Housing, raising the per capita water demand from 75 l/p/d to 150l/p/d and maintaining the ones in the High-Classs Housing (HCH) at 250 l/p/d. An average water use rate of 156 l/p/d was then used in the high living standard scenario. This high living scenario presents the highest water demand in comparison to other scenarios considered (Figure 4.10). The water demand in this scenario is 763Mm^3 against 605 Mm^3 of the reference scenario in the year 2040.

This implies that as the government strives to better the living standard for its population within the city, it should encourage water saving tips to ensure the growth is not directly proportionate with the increased living standard. This is possible as Denmark has progressively reduced its water demand from 136 l/p/d in 1997 to 104l/p/d in 2016 despite the improved living standard (EurEau , 2017).

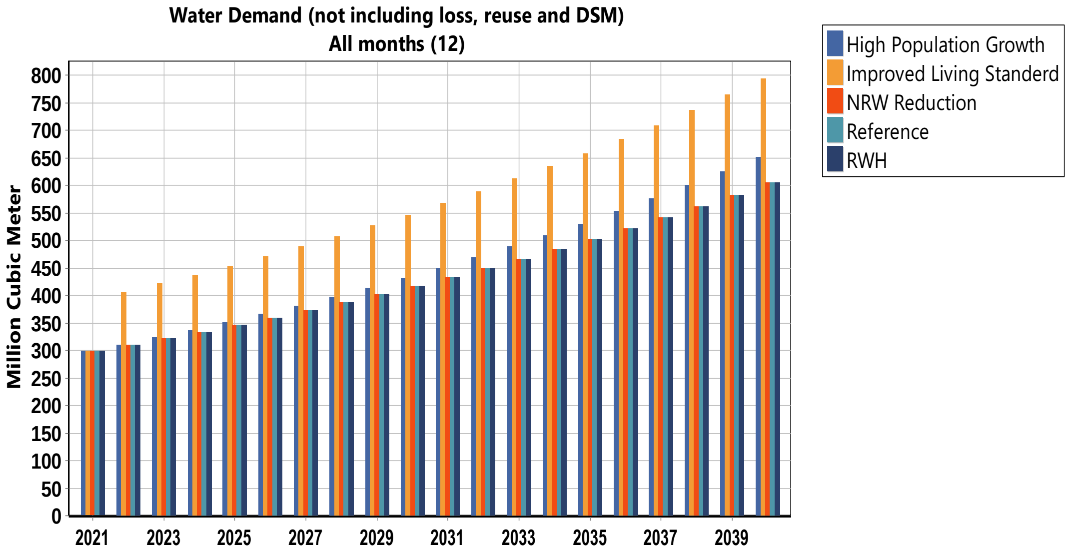


Figure 4.10: Demand under the HLS in Comparison to others.

4.4.3 High Population Growth (HPG) scenario

In this scenario instead of the 3.8% population growth rate adopted in the “business as usual scenario”, 4.2 % growth was used to represent the rapid population growth. The simulation results showed that the HPG rate and business as usual scenarios have a similar trend, however, the demand coverage for the HPG scenario is considerably lower than the reference scenario (Figure 4.11).

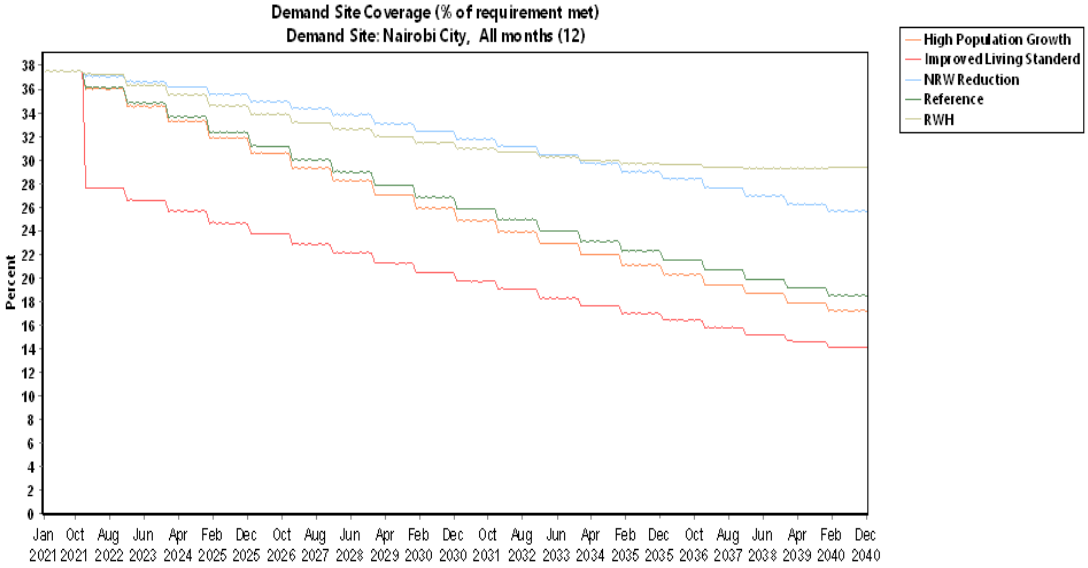


Figure 4.11: Demand coverage under the reference and other future scenarios

The HPG scenario shows that the city will only cover 17% of the demand in 2040, compared to around 19% under the reference scenario in that same year. As a result of this low demand coverage problem, the unmet demand of Nairobi city in this scenario will reach 1,036Mm^3 by 2040 as the maximum amount under this scenario (table 4.7). The results show that the high population growth comes second on the impact it has on the unmet water demand.

Table 4.7: Unmet Water demand (in m^3) under reference and other scenarios.

	2021	**2025**	**2030**	**2035**	**2040**
High Population Growth	357,754,793	460,214,638	614,444,990	803,896,516	1,036,032,121
Improved Living Standard	357,754,793	656,658,126	835,355,566	1,050,685,843	1,309,572,659
NRW Reduction	357,754,793	389,941,647	448,150,332	526,056,442	624,451,642
Reference	357,754,793	449,909,211	586,223,284	750,478,043	947,826,823
RWH	357,754,793	434,729,211	549,227,284	678,750,636	821,616,823

This result as much as it is not far away from the reference scenario, the city should avoid situations that worsen the already low water coverage percent. The analysis of the city population in relation to the unmet water demand, shows that the city is likely to acute water shortage if the population growth increases with the on-going urbanization and industrialization together with rural to city migration.

4.4.4 Rain Water Harvesting (RWH) scenario

The amount of rain water harvested in this was based on the population increase with each increased person representing $17m^2$, this corresponds to rainfall volume of 10.2 m^3 per person per month. The yield from rainfall was then calculated using the rainfall run-off coefficient and annual rainfall based on the rainfall probability in Nairobi. From the analysis implementation of RWH Scenario will reduce the unmet water demand by $126Mm^3$ by the year 2040 this will increase the demand coverage from 19% to 29% in the same year (figure 4.12).

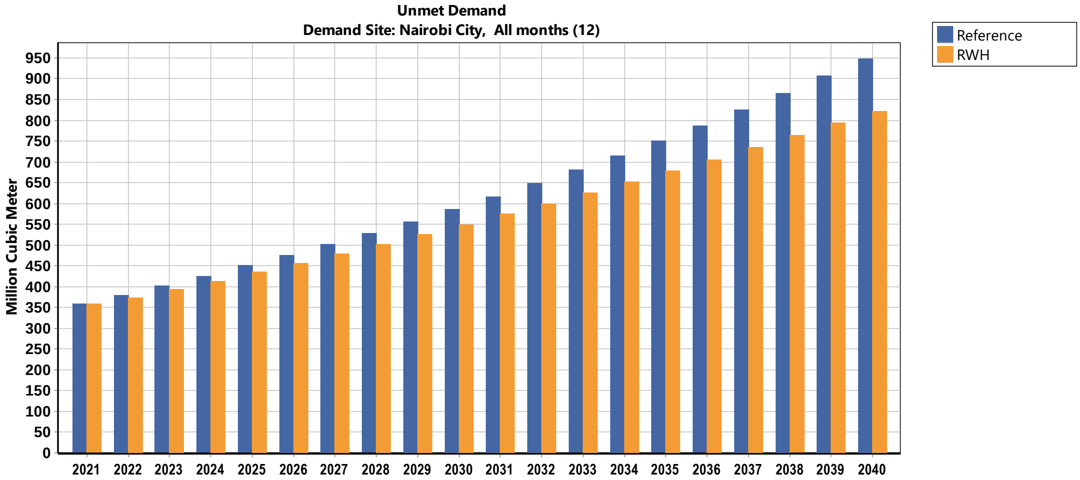


Figure 4.122: Demand coverage under the reference and other future scenarios

Introducing RWH will introduce an additional water volume of 126Mm^3 by the year 2040, bringing the combined water supply delivered to 342Mm^3 by 2040 (Figure 4.13). This is much more than the supply coming from the Sasumua system which is the second largest supply source. RWH if well harnessed can be the second largest water supply for the city from the analysis.

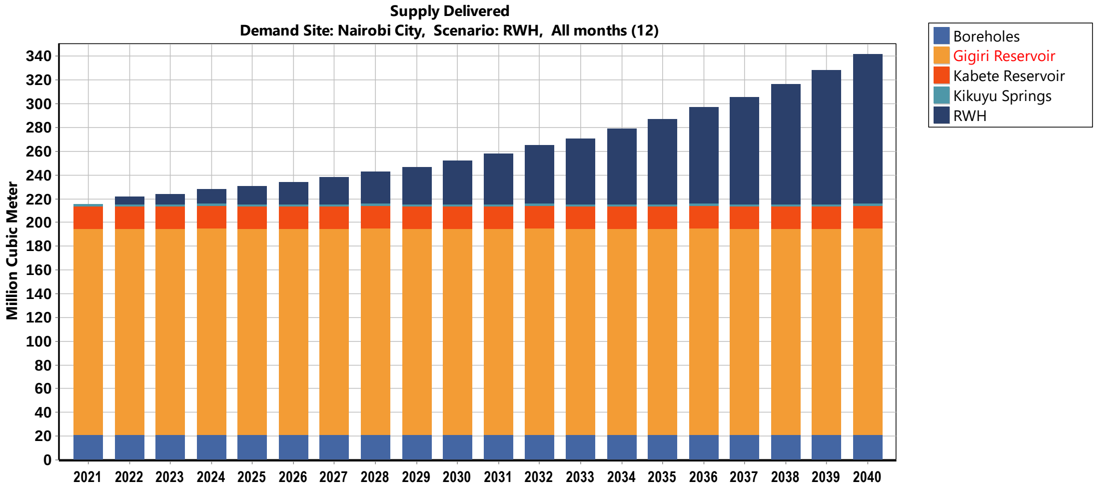


Figure 4.13: Supply delivered under RWH in comparison to Reference Scenario

4.4.5 Combined Rain Water Harvesting (RWH) and NRW reduction scenario

Combining the rain water harvesting and the non-revenue water reduction strategy has the greatest impact on the unmet demand (Table 4.8). The unmet water demand considerably drops from 947Mm3 in the reference scenario to 552Mm3 by the year 2040.

Table 4.8: Unmet water demand combined RWH and NRW reduction scenarios.

	2021	2025	2030	2035	2040
Combined HPG and HLS Scenario	357,754,793	670,172,573	872,351,620	1,120,708,710	1,425,203,133
Combined RWH and NRW Scenario	357,754,793	383,907,033	433,207,900	491,357,102	552,355,772
High Population Growth	357,754,793	460,214,638	614,444,990	803,896,516	1,036,032,121
Improved Living Standard	357,754,793	656,658,126	835,355,566	1,050,685,843	1,309,572,659
NRW Reduction	357,754,793	389,941,647	448,150,332	526,056,442	624,451,642
Reference	357,754,793	449,909,211	586,223,284	750,478,043	947,826,823
RWH	357,754,793	434,729,211	549,227,284	678,750,636	821,616,823

This improved figures in the unmet water demand has the corresponding increase in demand coverage from 19% in reference scenario to 39% (Figure 4.14). From the analysis, the demand coverage under this combined scenario is even more than the demand coverage in the current year of 2021.

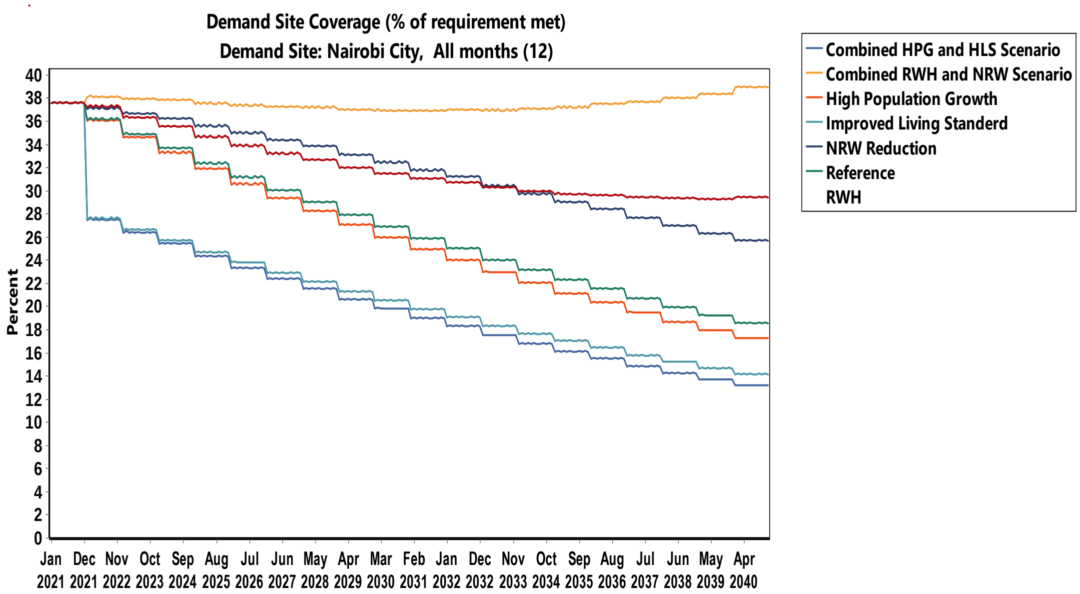


Figure 4.14: Demand site coverage under the RWH and NRW reduction scenarios.

4.4.6 Combined High Living Standard (HLS) and High Population Growth Scenario

Combining the improved living standard and the rapidly growing population will have a very adverse effect on the unmet water demand. In this combined future scenario, the unmet water demand is expected to surpass the one in the reference scenario by 477Mm^3 by 2040 (Figure 4.15).

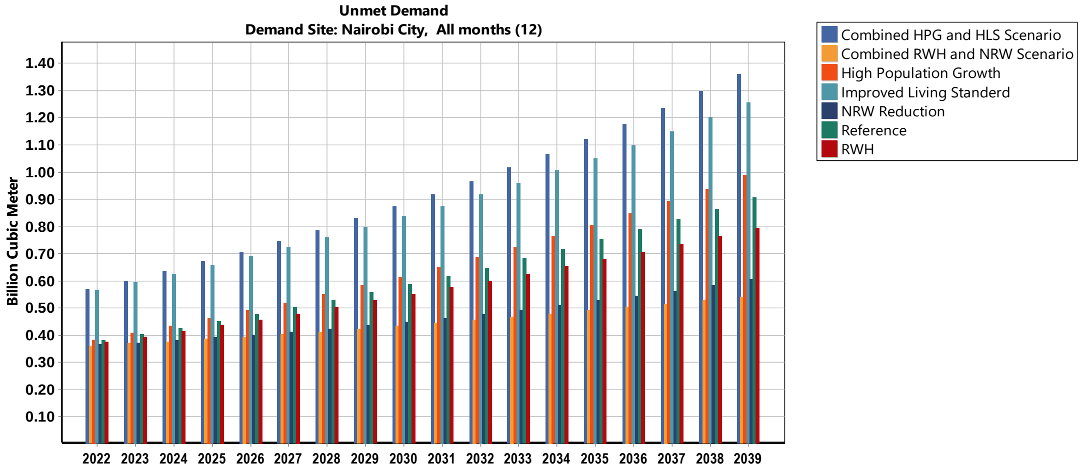


Figure 4.15: Unmet water demand for different scenarios

By maintaining the NRW at 48% in this combined scenario, the water supply requirement is expected to rise from 1,1633Mm^3 in the reference scenario to 1,641Mm^3 (table 4.9). Showing that the water supply requirements in this scenario will be three times the one in the current year.

Table 4.9: Unmet water demand combined RWH and NRW reduction scenarios.

	2021	**2025**	**2030**	**2035**	**2040**
Combined HPG and HLS Scenario(m^3)	357,754,793	670,172,573	872,351,620	1,120,708,710	1,425,203,133
Reference(m^3)	357,754,793	449,909,211	586,223,284	750,478,043	947,826,823

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The main objective of this study was to create the Water Evaluation and Planning (WEAP) model for simulating the current water supply system in Nairobi city. The model was then used to analyse various scenarios for Management and external change. The results from the model were used to create water management strategies for the city's future water supply in response to its rising water demand. The model's analytical outcomes allow for the following inferences:

i. The calibration and validation statistical results, R^2, NSE, RSR, and PBIAS (0.70,0.98,0.5, and 2.0 respectively), showed that the model was well adapted to the catchment and able to represent its hydrological behavior. The lack of data, however, made it difficult to calibrate and validate the model for streamflow.

ii. The findings indicated that Nairobi City's average demand coverage will decline progressively if there are no deliberate efforts to tame the ever-increasing unmet water demand in the business-as-usual scenario.

iii. From the results, the water demand is projected to increase from 298 Mm3 in 2021 to 605 Mm^3 in the year 2040. This will translate to an average city unmet demand of 948 Mm^3 by the year 2040. Majorly the high unmet demand being contributed by the NRW.

iv. According to the model results, adding Rain Water Harvesting (RWH) to the supply system will increase the annual water demand coverage of the city as compared to the reference scenario. In 2040, under the RWH scenario, the average water-demand coverage and unmet demand will be 29% and 822 Mm3, respectively.

v. By reducing the Non-Revenue Water under the NRW Control scenario, Results indicate a significant improvement in the city water demand coverage as compared to the reference scenario.

vi. By combining the Non-Revenue Water (NRW) reduction scenario and Rain Water Harvesting scenario the unmet water demand will significantly be reduced due to better demand coverage than the one under the reference scenario. By 2040, the city will be unable to meet an additional 395 Mm^3 of its demand representing a 20% (19% to 39%) rise in the demand coverage as compared to the reference scenario.

vii. High living standards coupled with high population growth will hurt the demand coverage of the city. In this scenario, the model predicted that the demand coverage will be only 13% by 2040 while the unmet water demand will be the highest at 1,425 Mm^3 same year.

5.2 Recommendations

i. From the improved water demand coverage occasioned by the in-cooperation of rainwater harvesting, the county government together with other institutional stakeholders can partner in putting up appropriate legislation and policies to have rainwater harvesting as a requirement for future building approval.

ii. The service provider within the city should have a proactive approach to the reduction of Non-Revenue Water as this has a big impact on the water demand coverage and unmet water demand. Having high non-revenue water will greatly compromise the already worse water situation in the city.

iii. The water service provider together with other key stakeholders should sensitize the public on water-saving practices to minimize water consumption as the living standards improve.

iv. The findings of the scenario analysis in this study may be used in forming an agenda for deliberation of water management professionals, planners in the water sector, and county government about management strategies for enhancing the city's water supply.

v. The government should, in the spirit of devolution, create more job opportunities at the county level to minimize the influx of people migrating to the capital city to seek job opportunities.

REFERENCES

Abdo, R. U. (2009). Evaluation of Urban Water Supply Options Using WEAP: The Case of Nablus City. Master Degree, Thesis, An-Najah National University, Nablus, Palestine.

Abera .A. D., & Ayenew. T. (2021). Evaluation of the WEAP model in simulating sub-basin hydrology in the Central Rift Valley basin, Ethiopia.

Aladenola, O. O., & Adeboye, O. B. (2010). Assessing the potential for rainwater harvesting. *Water resources management*, 24(10), 2129-2137.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop Evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, 300, 6541.

Asghar, A., Iqbal, J., Amin, A., & Ribbe, L. (2019). Integrated hydrological modeling for assessment of water demand and supply under socio-economic and IPCC climate change scenarios using WEAP in Central Indus Basin. *Journal of Water Supply: Research and Technology-Aqua*, 68(2), 136-148.

Aung. Z. W. (2014). Water supply options for the growing megacity of Yangon - scenarios with the WEAP model.

Ayele, A. S. (2016). Application of water evaluation and allocation planning (WEAP) model to assess future water demands and water balance of the Caledon river basin (Doctoral dissertation, Bloemfontein: Central University of Technology, Free State).

Chow, V.T., Maidment D. R., and Mays W. L. (1988). *Applied Hydrology*, McGraw Hill, Singapore Fong and Sons Printers.

Dienya, R.N. (2007). application of the weap model in integrated water resources management of the Nyando River Basin, Kenya

Eryani.I.G.A.P., Jayantari.M.W., Wijaya.M.K.I. (2022). "Sensitivity Analysis in Parameter Calibration of the WEAP Model for Integrated Water Resources Management in Unda Watershed," Civil Engineering and Architecture, Vol. 10, No. 2, pp. 455-469, 2022. DOI: 10.13189/cea.2022.100206.

EurEau. (2017). Europe’s Water in Figures: An Overview of the European Drinking Water and Waste Water Sectors.

Fletcher TD, Deletic A, Mitchell VG, Hatt BE (2008). Reuse of urban runoff in Australia: a review of recent advances and remaining challenges.

Giupponi, C., Mysiak, J., Fassio, A., and Cogan, V. (2004). MULINO-DSS: A computer tool for sustainable use of water resources at the catchment scale, Math. *Comput. Simul.*, 64, 13–24, 2004.

Gupta, H. V., Sorooshian, S., & Yapo, P. O. (1999). Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of hydrologic engineering*, 4(2), 135-143.

Haasjes.E. (2012). An exploratory research to the usability of WEAP and measures for potential water savings in Campo de Cartagena irrigation district, SE Spain

Haughton, G., & Hunter, C. (2004). *Sustainable Cities*. Routledge.

Immerzeel, W. W., & Droogers, P. (2008). Calibration Methodologies in Hydrological modelling: State of the Art.

Ingol-Blanco E, McKinney .D.C .(2013). Development of a hydrological model for the Rio Conchos Basin. *J Hydrol Eng* 18(3):340–351. https://doi.org/10.1061/(ASCE)he.1943-5584.0000607

Kenya, Japanese International Cooperation Agency (JICA), National Water Master Plan (NWMP), Nairobi, Kenya, (2013).

Kenya, Japanese International Cooperation Agency (JICA), The Project on Integrated Urban Development Master Plan for the City of Nairobi in the Republic of Kenya (2014).

Kenya, Ministry of Water and Irrigation (MoWI), (2005). Practice Manual for Water Supply Services in Kenya. Kenya-Belgium Study and Consultancy Fund, Nairobi, Kenya.

Kenya, National Bureau of Statistics. (2009) Kenya Population and Housing Census Reports. Government Printer, Nairobi, Kenya, (2010).

Kenya, National Bureau of Statistics. (2019). Kenya Population and Housing Census Reports. Government Printer, Nairobi, Kenya, (2020).

Kooke, S.O., Sumba, L.A., & Kurgat, P. (2012). Rainwater harvesting for drought mitigation and food security in Magadi Division, Kajiado. C.O.Misati (Ed.), Hydrological Society of Kenya Proceedings. Kenyatta University.

Legesse, D., Vallet-Coulomb, C., & Gasse, F. (2003). Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of hydrology*, 275(1-2), 67-85.

Leong, W. K., & Lai, S. H. (2017, June). Application of water evaluation and planning model for integrated water resources management: case study of Langat river basin, Malaysia. In IOP Conference Series: Materials Science and Engineering (Vol. 210, No. 1, p. 012024). IOP Publishing.

Loucks, D. P. (2006). Generic simulation models for facilitating stakeholder involvement in water resources planning and management: a comparison, evaluation, and identification of future needs. In Proceedings of the iEMSs third biennial meeting: “Summit on Environmental Modelling and Software”, Burlington.

Malla, M. A., Ahmad, U. F., Rather, M. A., Teli, M. N., & Kuchhay, N. A. (2014). Assessing water demand and supply for Srinagar City (J&K) India, under changing climatic scenarios using water evaluation and planning model (WEAP).

McCartney, M. P., & Arranz, R. (2007). Evaluation of historic, current, and future water demand in the Olifants River Catchment, South Africa (Vol. 118). IWMI.

Mitullah. W. (2003). Urban slums reports: The case of Nairobi, Kenya.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE,* 50(3), 885-900.

Mugatsia, E. A. (2010). Simulation and scenario analysis of water resources management in Perkerra catchment using WEAP model. M asters Thesis, Department of Civil and Structural Engineering, School of Engineering, Moi University, Kenya, (December).

Muraguri, P. M. (2016). Assessment of Groundwater Quality in Nairobi County, Kenya (Doctoral dissertation, Environmental Legislation and Management, JKUAT).

Mutua, B.M.; Mourad, K.A.; & Oduor, B.O. (2018). Uncertainty analysis and calibration of SWAT modelfor estimating impacts of conservation methods on streamflow and sediment yield in Thika River catchment, Kenya. *Int. J. Hydrol. Res.* 2018,3, 1–11.

Nabinejad, S., Jamshid Mousavi, S., & Kim, J. H. (2017). Sustainable basin-scale water allocation with hydrologic state-dependent multi-reservoir operation rules. *Water Resources Management*, 31(11), 3507-3526.

Nairobi County Integrated Development Plan (NCIDP) 2014.

Nairobi water. (2019). Nairobi City Water and Sewerage Company Strategic Plan 2019/2020-2023/2024). Strategic planning. Nairobi: Nairobi water.

Nyika J, G.N. Karuku, & Onwonga. R. N., (2017). Modelling water demand and efficient use in Mbagathi sub-catchment using WEAP

Okungu, J., Adeyemo, J., & Otieno, F. (2017). Scenario analysis of water supply and demand using WEAP model: a case of Yala catchment, Kenya. *American Journal of Water Resources,* 5(4), 125-131.

Osoro, G. M., Mourad, K. A., & Ribbe, L. (2018). Water demand simulation using WEAP 21: a case study of the Mara River Basin, Kenya.

Ramadan, S. M., Negm, A. M., & Owais, T. M. (2011). Effect of new upper Nile projects on the integrated management of the basin: Review and Methodology. In Fifteenth International Water Technology Conference, IWTC-15.

Santhi, C., Arnold, J., Williams, J. R., Dugas, W. A., Srinivasan, R., & Hauck, L. M. (2001). Validation of the SWAT Model on a Large River Basin with Point and Nonpoint Sources. *JAWRA*, 37, 1169-1188.

SEI. (2011). WEAP Water Evaluation and Planning System: User Guide for WEAP21. Stockholm Environment Institute, Boston.

Shuetze. T. and Fandino. V. (2013). Quantitative Assessment of Water Use Efficiency in Urban and Domestic Buildings. ISSN 2073-4441.

Silva, F. B., Pereira, S. B., Vieira, E. D. O., Pereira, D. D. R., & de MC Passos, J. B. (2017). Sensitivity Analysis of the Water Balance Components of the WEAP Model for the High Rio Verde Grande Basin/mg.

United Nations, population division, department of economic and social affairs, New York, 2017 - World Urbanisation Prospects: New York: population division, department of economic and social affairs, United Nations.

Water Services Regulatory Board (2018); Impact report: A Performance Report of Kenya’s Water Services Sub-Sector, Issue No 12. Nairobi, Kenya.

World Water Assessment Programme (Nations Unies), The United Nations World Water Development Report 2018 (United Nations Educational, Scientific and Cultural Organization, New York, United States) .

WWAP (UNESCO World Water Assessment Programme). 2018. The United Nations World Water Development Report 2018: Leaving No One Behind. Paris, UNESCO."

Yates. D, Sieber.J, Purkey.D. & Annette .H. L. (2005). WEAP21—A Demand-, Priority, and Preference-Driven Water Planning Model, *Water International*, 30:4, 487-500

APPENDICES

Appendix A: Results for Observed and simulated reservoir volumes

Month/yr	Observed Vol.(m^3)	Simulated Vol.(m^3)	Month/yr	Observed Vol.(m^3)	Simulated Vol.(m^3)
Jan-97	70,000,000	65,319,355	Jan-07	70,000,000	70,000,000
Feb-97	62,300,000	60,769,813	Feb-07	69,800,000	69,213,401
Mar-97	58,900,000	56,127,388	Mar-07	67,500,000	65,684,416
Apr-97	54,700,000	70,000,000	Apr-07	65,100,000	70,000,000
May-97	69,000,000	70,000,000	May-07	69,700,000	70,000,000
Jun-97	70,000,000	70,000,000	Jun-07	70,000,000	70,000,000
Jul-97	70,000,000	70,000,000	Jul-07	70,000,000	70,000,000
Aug-97	70,000,000	68,726,613	Aug-07	70,000,000	70,000,000
Sep-97	67,600,000	65,017,618	Sep-07	70,000,000	68,648,829
Oct-97	58,500,000	70,000,000	Oct-07	70,000,000	69,807,257
Nov-97	70,000,000	70,000,000	Nov-07	70,000,000	70,000,000
Dec-97	70,000,000	70,000,000	Dec-07	69,500,000	66,885,203
Jan-98	70,000,000	70,000,000	Jan-08	66,500,000	62,452,589
Feb-98	70,000,000	70,000,000	Feb-08	62,200,000	56,359,225
Mar-98	70,000,000	70,000,000	Mar-08	55,200,000	50,480,082
Apr-98	70,000,000	70,000,000	Apr-08	50,900,000	55,798,369
May-98	70,000,000	70,000,000	May-08	54,300,000	54,610,565
Jun-98	70,000,000	70,000,000	Jun-08	54,600,000	51,576,598
Jul-98	69,000,000	70,000,000	Jul-08	52,200,000	48,016,552
Aug-98	69,000,000	68,934,447	Aug-08	49,400,000	43,750,010
Sep-98	69,000,000	66,179,716	Sep-08	47,100,000	39,384,957
Oct-98	61,900,000	61,824,423	Oct-08	44,600,000	40,360,098
Nov-98	58,900,000	63,226,299	Nov-08	48,600,000	51,273,462
Dec-98	55,400,000	59,035,901	Dec-08	52,800,000	49,441,437
Jan-99	51,900,000	54,793,982	Jan-09	50,600,000	45,184,337
Feb-99	45,700,000	49,566,474	Feb-09	45,900,000	39,539,780
Mar-99	39,600,000	46,739,450	Mar-09	40,000,000	33,847,768
Apr-99	37,800,000	52,795,319	Apr-09	35,000,000	32,104,473
May-99	48,300,000	55,853,199	May-09	32,100,000	34,229,453
Jun-99	51,900,000	54,941,690	Jun-09	33,700,000	32,508,996
Jul-99	50,200,000	51,599,414	Jul-09	32,900,000	29,997,387
Aug-99	48,300,000	47,967,535	Aug-09	31,700,000	27,817,467
Sep-99	44,700,000	43,888,449	Sep-09	30,400,000	26,013,272
Oct-99	39,600,000	39,613,806	Oct-09	31,100,000	32,689,164
Nov-99	34,600,000	44,919,628	Nov-09	42,300,000	41,658,655
Dec-99	50,200,000	65,466,429	Dec-09	51,000,000	47,392,125
Jan-00	56,800,000	63,202,720	Jan-10	58,400,000	58,560,825
Feb-00	52,000,000	58,745,284	Feb-10	64,400,000	64,250,313
Mar-00	48,300,000	53,122,115	Mar-10	67,900,000	70,000,000
Apr-00	41,700,000	49,294,478	Apr-10	70,000,000	70,000,000
May-00	37,800,000	44,964,308	May-10	70,000,000	70,000,000

Jun-00	34,600,000	41,995,514	Jun-10	70,000,000	70,000,000
Jul-00	31,400,000	39,071,877	Jul-10	70,000,000	70,000,000
Aug-00	29,100,000	35,828,848	Aug-10	68,600,000	67,685,109
Sep-00	24,600,000	32,564,494	Sep-10	65,900,000	63,359,765
Oct-00	24,000,000	29,459,810	Oct-10	63,400,000	63,897,022
Nov-00	23,700,000	30,102,434	Nov-10	68,500,000	66,309,118
Dec-00	24,600,000	31,608,366	Dec-10	70,000,000	68,573,227
Jan-01	30,600,000	41,742,856	Jan-11	69,200,000	65,619,991
Feb-01	45,100,000	41,903,968	Feb-11	66,600,000	61,633,598
Mar-01	45,100,000	43,519,397	Mar-11	63,000,000	60,117,687
Apr-01	46,900,000	50,209,468	Apr-11	59,800,000	63,473,502
May-01	70,000,000	59,195,792	May-11	63,000,000	70,000,000
Jun-01	70,000,000	62,679,216	Jun-11	66,600,000	70,000,000
Jul-01	70,000,000	59,494,719	Jul-11	66,700,000	67,671,096
Aug-01	69,900,000	56,141,663	Aug-11	64,700,000	65,506,696
Sep-01	64,000,000	51,891,542	Sep-11	63,000,000	63,810,120
Oct-01	58,900,000	47,077,760	Oct-11	63,300,000	70,000,000
Nov-01	56,000,000	47,198,010	Nov-11	70,000,000	70,000,000
Dec-01	56,000,000	45,234,188	Dec-11	70,000,000	70,000,000
Jan-02	52,800,000	42,158,365	Jan-12	69,600,000	69,438,021
Feb-02	49,400,000	38,010,527	Feb-12	67,000,000	66,156,678
Mar-02	45,800,000	34,468,853	Mar-12	62,700,000	59,658,944
Apr-02	43,500,000	49,900,487	Apr-12	58,100,000	68,639,194
May-02	70,000,000	65,635,957	May-12	67,500,000	70,000,000
Jun-02	70,000,000	67,968,146	Jun-12	70,000,000	70,000,000
Jul-02	69,300,000	68,278,116	Jul-12	70,000,000	69,934,129
Aug-02	69,200,000	65,816,120	Aug-12	70,000,000	70,000,000
Sep-02	64,000,000	62,320,113	Sep-12	69,700,000	67,133,639
Oct-02	58,900,000	62,354,503	Oct-12	68,700,000	69,224,427
Nov-02	63,000,000	69,396,472	Nov-12	70,000,000	70,000,000
Dec-02	70,000,000	70,000,000	Dec-12	70,000,000	70,000,000
Jan-03	70,000,000	70,000,000	Jan-13	69,900,000	67,371,409
Feb-03	70,000,000	68,292,242	Feb-13	68,800,000	67,043,828
Mar-03	66,600,000	63,817,395	Mar-13	64,800,000	66,237,527
Apr-03	63,600,000	67,883,163	Apr-13	68,200,000	64,459,327
May-03	70,000,000	70,000,000	May-13	70,000,000	59,800,716
Jun-03	70,000,000	70,000,000	Jun-13	69,800,000	60,851,314
Jul-03	70,000,000	70,000,000	Jul-13	67,900,000	57,036,594
Aug-03	70,000,000	70,000,000	Aug-13	64,400,000	53,548,565
Sep-03	69,000,000	67,743,785	Sep-13	59,600,000	49,732,314
Oct-03	66,600,000	67,040,273	Oct-13	54,800,000	47,280,521
Nov-03	68,300,000	70,000,000	Nov-13	51,100,000	51,877,621
Dec-03	70,000,000	70,000,000	Dec-13	53,500,000	53,417,691
Jan-04	69,000,000	68,276,316	Jan-14	59,000,000	50,993,750
Feb-04	66,600,000	66,363,912	Feb-14	56,700,000	46,510,553
Mar-04	62,400,000	62,952,752	Mar-14	53,700,000	43,348,851
Apr-04	70,000,000	70,000,000	Apr-14	53,200,000	48,347,717
May-04	70,000,000	70,000,000	May-14	58,000,000	62,326,432

Jun-04	70,000,000	70,000,000	Jun-14	63,300,000	67,712,091
Jul-04	69,000,000	67,086,619	Jul-14	66,200,000	66,040,371
Aug-04	67,000,000	62,448,133	Aug-14	64,300,000	61,935,124
Sep-04	59,900,000	57,650,195	Sep-14	61,800,000	56,158,441
Oct-04	54,900,000	54,223,041	Oct-14	59,200,000	54,288,695
Nov-04	59,900,000	58,479,845	Nov-14	62,800,000	70,000,000
Dec-04	66,400,000	57,010,471	Dec-14	69,800,000	70,000,000
Jan-05	65,800,000	54,135,156	Jan-15	67,500,000	68,999,922
Feb-05	63,700,000	50,473,874	Feb-15	61,400,000	63,826,814
Mar-05	59,200,000	45,896,035	Mar-15	53,500,000	55,374,162
Apr-05	58,100,000	49,357,429	Apr-15	47,400,000	63,381,218
May-05	65,800,000	70,000,000	May-15	57,300,000	70,000,000
Jun-05	70,000,000	70,000,000	Jun-15	69,800,000	70,000,000
Jul-05	70,000,000	70,000,000	Jul-15	69,300,000	68,224,399
Aug-05	70,000,000	68,793,957	Aug-15	66,500,000	63,142,926
Sep-05	69,800,000	66,072,889	Sep-15	60,700,000	55,765,272
Oct-05	66,900,000	64,274,076	Oct-15	53,700,000	48,823,817
Nov-05	64,700,000	64,793,227	Nov-15	56,600,000	51,924,027
Dec-05	62,700,000	60,246,638	Dec-15	69,300,000	53,288,799
Jan-06	59,300,000	55,201,781	Jan-16	69,700,000	53,067,346
Feb-06	53,800,000	49,464,167	Feb-16	68,900,000	51,796,978
Mar-06	48,400,000	45,060,519	Mar-16	66,100,000	46,633,358
Apr-06	44,700,000	53,895,250	Apr-16	66,100,000	54,521,038
May-06	60,800,000	70,000,000	May-16	69,700,000	62,089,580
Jun-06	70,000,000	70,000,000	Jun-16	69,900,000	63,586,722
Jul-06	68,600,000	67,868,261	Jul-16	67,500,000	57,624,600
Aug-06	63,700,000	65,432,457	Aug-16	61,800,000	50,452,963
Sep-06	60,800,000	60,721,256	Sep-16	54,600,000	42,620,658
Oct-06	55,900,000	56,631,850	Oct-16	47,200,000	34,441,827
Nov-06	54,100,000	64,115,814	Nov-16	39,300,000	31,158,887
Dec-06	69,500,000	70,000,000	Dec-16	34,600,000	24,627,949

Appendix B: Results for supply requirement under different scenarios

	Reference	HPG	HLS	NRW Red	RWH
2021	572,794,793	572,794,793	572,794,793	572,794,793	572,794,793
2022	594,560,995	596,852,174	779,424,497	579,581,054	594,560,995
2023	617,154,313	621,919,965	809,042,628	587,224,303	617,154,313
2024	640,606,176	648,040,604	839,786,248	595,697,912	640,606,176
2025	664,949,211	675,258,309	871,698,126	604,981,647	664,949,211
2026	690,217,281	703,619,158	904,822,654	615,060,757	690,217,281
2027	716,445,538	733,171,163	939,205,915	625,925,238	716,445,538
2028	743,670,468	763,964,352	974,895,740	637,569,237	743,670,468
2029	771,929,946	796,050,854	1,011,941,778	649,990,573	771,929,946
2030	801,263,284	829,484,990	1,050,395,566	663,190,332	801,263,284
2031	831,711,289	864,323,360	1,090,310,597	677,172,553	831,711,289
2032	863,316,318	900,624,941	1,131,742,400	691,943,957	863,316,318
2033	896,122,338	938,451,189	1,174,748,611	707,513,732	896,122,338
2034	930,174,987	977,866,138	1,219,389,058	723,893,353	930,174,987
2035	965,521,636	1,018,936,516	1,265,725,843	741,096,442	965,521,636
2036	1,002,211,458	1,061,731,850	1,313,823,425	759,138,645	1,002,211,458
2037	1,040,295,494	1,106,324,588	1,363,748,715	778,037,537	1,040,295,494
2038	1,079,826,723	1,152,790,220	1,415,571,166	797,812,554	1,079,826,723
2039	1,120,860,138	1,201,207,410	1,469,362,870	818,484,927	1,120,860,138
2040	1,163,452,823	1,251,658,121	1,525,198,659	840,077,642	1,163,452,823

Appendix C: Results for unmet water demand under different Scenarios

	Reference	**HPG**	**HLS**	**NRW Red**	**RWH**
2021	357,754,793	357,754,793	357,754,793	357,754,793	357,754,793
2022	379,520,995	381,812,174	564,381,239	364,541,054	373,112,995
2023	402,114,313	406,879,965	594,002,628	372,183,918	393,073,313
2024	424,980,176	432,414,604	624,160,248	380,071,912	412,993,176
2025	449,909,211	460,214,638	656,658,126	389,941,647	434,729,211
2026	475,177,271	488,579,158	689,782,654	400,020,757	456,431,281
2027	501,405,538	518,131,018	724,165,915	410,884,663	478,728,538
2028	528,044,468	548,338,352	759,269,740	421,943,237	500,972,468
2029	556,889,946	581,010,854	796,901,778	434,950,504	525,122,946
2030	586,223,284	614,444,990	835,355,566	448,150,332	549,227,284
2031	616,671,289	649,281,997	875,270,597	462,131,028	573,931,289
2032	647,690,318	684,998,941	916,116,400	476,317,957	598,526,318
2033	681,082,338	723,411,189	959,708,611	492,473,732	625,153,338
2034	715,134,987	762,826,138	1,004,349,058	508,853,353	651,659,987
2035	750,478,043	803,896,516	1,050,685,843	526,056,442	678,750,636
2036	786,585,458	846,102,767	1,098,197,425	543,512,645	705,608,458
2037	825,255,494	891,284,588	1,148,708,507	562,997,537	734,651,494
2038	864,786,723	937,750,220	1,200,531,166	582,772,554	763,423,723
2039	905,820,138	986,167,410	1,254,322,870	603,444,927	792,730,138
2040	947,826,823	1,036,032,121	1,309,572,659	624,451,642	821,616,823

Appendix D: Climatic Data (from Thika and Thika dam stations)

Year	Month	Evap[mm]	Precip[mm]	T_mean[C]	Humidity[%]	Wind[m/sec]
1997	Jan	124.16	39.5	24	79	2.3
1997	Feb	133.45	1.1	28	75	2.4
1997	Mar	64.88	94.5	26	72	2.3
1997	Apr	-11.7	592.1	25	85	2.1
1997	May	-95	269.1	23	91	1.9
1997	Jun	68.32	105.3	20	85	2.3
1997	Jul	125.62	59.9	21	81	2.3
1997	Aug	55.52	52.5	19	84	2.5
1997	Sep	57.71	8.4	21	76	2.4
1997	Oct	-205.3	478.5	23	85	2.7
1997	Nov	-63.43	574	22	89	2
1997	Dec	-76.51	161.3	23	91	1.9
1998	Jan	200.9	543.6	24	83	2.1
1998	Feb	62.13	237.3	26	84	2.1
1998	Mar	113.93	224.1	26	90	1.9
1998	Apr	-2.82	469.6	24	92	2.2
1998	May	-35.51	552.6	22	92	2.1
1998	Jun	-100.9	155.7	21	90	2
1998	Jul	-7.54	60.7	21	89	1.9
1998	Aug	42.27	71.7	20	82	1.9
1998	Sep	94.66	76.3	22	76	2.1
1998	Oct	26.77	57.5	23	77	2
1998	Nov	101.36	271.1	23	83	1.9
1998	Dec	79.426	19.3	24	76	2.1
1999	Jan	135.92	69.1	27	70	2.4
1999	Feb	169.4	9.7	27	59	2.4
1999	Mar	135.9	255.5	28	69	2.1
1999	Apr	-57.75	315.6	27	78	2.1
1999	May	62.15	87.2	23	82	2.4
1999	Jun	114.67	11.6	22	83	1.8
1999	Jul	60.24	63.3	19	80	1.9
1999	Aug	-24.49	54.6	20	83	1.9
1999	Sep	-22.6	27.2	24	79	2.1
1999	Oct	-251.33	89.7	24	77	2.3
1999	Nov	-79.04	411.8	24	81	1.9
1999	Dec	15.99	462.4	23	79	2
2000	Jan	142.923	5.6	24	60	2.8
2000	Feb	122.67	4.2	26	64	2.6
2000	Mar	167.65	62	25	61	2.6
2000	Apr	216.75	161.3	24	80	2.1
2000	May	471.16	105.2	25	84	2.1
2000	Jun	-12.06	34.1	20	84	1.8
2000	Jul	0.18	37.2	19	85	1.7
2000	Aug	19.04	27.8	18	78	1.9

2000	Sep	81.64	48.3	22	73	2.1
2000	Oct	-99.33	33.3	24	75	2.2
2000	Nov	27.14	268.8	22	81	1.9
2000	Dec	-17.29	172.8	22	79	1.9
2001	Jan	133.56	329.3	26	72	2.4
2001	Feb	132.92	26.3	25	64	2.2
2001	Mar	101.9	237.8	24	72	2.2
2001	Apr	283.96	284.8	23	81	1.8
2001	May	126.97	237.7	21	80	2.4
2001	Jun	-22.02	85.8	18	84	1.9
2001	Jul	115.54	15.4	17	81	1.9
2001	Aug	18.25	33.9	20	79	2.1
2001	Sep	-23.47	6.4	20	75	2
2001	Oct	100.6	84.3	23	72	2.3
2001	Nov	-12.14	232.6	22	78	1.9
2001	Dec	-75.7	103.1	23	79	1.8
2002	Jan	113.87	92.4	24	71	2.4
2002	Feb	19.59	34.6	28	69	2.2
2002	Mar	-9.4	158.6	26	73	2
2002	Apr	-14.32	574.6	25	76	2.2
2002	May	-30.16	323.45	23	79	2.5
2002	Jun	-28.48	45.7	20	81	2
2002	Jul	16.54	80.2	21	81	2
2002	Aug	-28.97	18.3	19	77	2.1
2002	Sep	37.68	75	21	75	2.2
2002	Oct	-104.256	252.9	23	77	2.3
2002	Nov	-138.298	251.4	22	77	2
2002	Dec	41.09	270.4	23	55	2
2003	Jan	137.34	39.2	24	59	2.3
2003	Feb	130.85	9	26	63	1.8
2003	Mar	180.32	70.6	26	76	2.3
2003	Apr	-167.46	342.8	24	81	1.8
2003	May	-142.63	452.7	22	77	2.1
2003	Jun	-13.21	191.5	21	78	1.7
2003	Jul	20.33	14	21	73	2.2
2003	Aug	3.58	166.05	20	68	2.3
2003	Sep	94.56	50.9	22	71	2.2
2003	Oct	-83.53	195.6	23	77	2.4
2003	Nov	-374.06	294.8	23	71	1.8
2003	Dec	-19.7	104.7	24	71	1.7
2004	Jan	-13.84	93.5	27	79	2.3
2004	Feb	19.63	129.4	27	75	2.4
2004	Mar	72.45	137	28	72	2.3
2004	Apr	-233.12	395.2	27	85	2.1
2004	May	-172.56	150.8	23	91	1.9
2004	Jun	-25.3	16.5	22	85	2.3
2004	Jul	41.84	7.6	19	81	2.3
2004	Aug	32.6	14.3	20	84	2.5

2004	Sep	76.8	55.3	24	76	2.4
2004	Oct	91.837	199	24	85	2.7
2004	Nov	-152.06	229.6	24	89	2
2004	Dec	71.57	86.8	23	91	1.9
2005	Jan	139.29	73.9	24	83	2.1
2005	Feb	101.44	16.5	26	84	2.1
2005	Mar	87	84.1	25	90	1.9
2005	Apr	-47.2	267.5	24	92	2.2
2005	May	-149.12	558.7	25	92	2.1
2005	Jun	51.88	86.2	20	90	2
2005	Jul	-21.68	86.1	19	89	1.9
2005	Aug	-29.71	35	18	82	1.9
2005	Sep	18.67	21.7	22	76	2.1
2005	Oct	-181.87	165.7	24	77	2
2005	Nov	-144.3	204.2	22	83	1.9
2005	Dec	80.62	12.1	22	76	2.1
2006	Jan	112.6	25.8	26	70	2.4
2006	Feb	148.53	8.1	25	59	2.4
2006	Mar	-177.04	161.8	24	69	2.1
2006	Apr	-370.56	432.9	23	78	2.1
2006	May	626.46	574.5	21	82	2.4
2006	Jun	-47.03	46.1	18	83	1.8
2006	Jul	-57.76	47.2	17	80	1.9
2006	Aug	27.69	109.5	20	83	1.9
2006	Sep	61.17	46.5	20	79	2.1
2006	Oct	28.297	140.2	23	77	2.3
2006	Nov	-42.4	372.3	22	81	1.9
2006	Dec	-62.67	285.1	23	79	2
2007	Jan	71.56	57	24	60	2.8
2007	Feb	83.7	41	28	64	2.6
2007	Mar	125.32	104.8	26	61	2.6
2007	Apr	45.61	403.2	25	80	2.1
2007	May	189.13	313.3	23	84	2.1
2007	Jun	-77.29	121.8	20	84	1.8
2007	Jul	36.82	107	21	85	1.7
2007	Aug	3.29	124.4	19	78	1.9
2007	Sep	74.95	58.5	21	73	2.1
2007	Oct	111.49	204.1	23	75	2.2
2007	Nov	92.39	138.6	22	81	1.9
2007	Dec	152.47	41.1	23	79	1.9
2008	Jan	83.38	71.9	24	72	2.4
2008	Feb	57.53	34.2	26	64	2.2
2008	Mar	124.16	204.8	26	72	2.2
2008	Apr	133.45	375	24	81	1.8
2008	May	64.88	68.5	22	80	2.4
2008	Jun	-11.7	24.7	21	84	1.9
2008	Jul	-95	44.1	21	81	1.9
2008	Aug	68.32	42.8	20	79	2.1

2008	Sep	125.62	33.9	22	75	2
2008	Oct	55.52	301.6	23	72	2.3
2008	Nov	57.7113	344.9	23	78	1.9
2008	Dec	-205.3	1.9	24	79	1.8
2009	Jan	124.16	49.3	27	79	2.3
2009	Feb	133.45	18.6	27	75	2.4
2009	Mar	64.88	113.9	28	72	2.3
2009	Apr	-11.7	212.2	27	85	2.1
2009	May	-95	185.8	23	91	1.9
2009	Jun	68.32	18.9	22	85	2.3
2009	Jul	125.62	6.3	19	81	2.3
2009	Aug	55.52	32.2	20	84	2.5
2009	Sep	57.71	61.25	24	76	2.4
2009	Oct	-205.3	375.9	24	85	2.7
2009	Nov	-63.43	246	24	89	2
2009	Dec	-76.51	153.5	23	91	1.9
2010	Jan	200.9	327.5	24	83	2.1
2010	Feb	62.13	155.8	28	84	2.1
2010	Mar	113.93	353.7	26	90	1.9
2010	Apr	-2.82	397.5	25	92	2.2
2010	May	-35.51	379.7	23	92	2.1
2010	Jun	-100.09	83.6	20	90	2
2010	Jul	-7.54	43.2	21	89	1.9
2010	Aug	42.27	56.7	19	82	1.9
2010	Sep	94.66	14.8	21	76	2.1
2010	Oct	26.77	262.6	23	77	2
2010	Nov	101.36	161.22	22	83	1.9
2010	Dec	79.426	178.8	23	76	2.1
2011	Jan	135.92	13	24	70	2.4
2011	Feb	169.4	75.4	26	59	2.4
2011	Mar	135.9	231.3	26	69	2.1
2011	Apr	-57.75	284.1	24	78	2.1
2011	May	62.15	222.5	22	82	2.4
2011	Jun	114.67	118.6	21	83	1.8
2011	Jul	60.24	49.5	21	80	1.9
2011	Aug	-24.49	82	20	83	1.9
2011	Sep	-22.6	112.7	22	79	2.1
2011	Oct	-251.33	406.94	23	77	2.3
2011	Nov	-79.04	362.9	23	81	1.9
2011	Dec	15.99	238.7	24	79	2
2012	Jan	142.92	18.2	27	60	2.8
2012	Feb	122.67	74.8	27	64	2.6
2012	Mar	167.65	0	28	61	2.6
2012	Apr	216.75	559.6	27	80	2.1
2012	May	471.16	866.6	23	84	2.1
2012	Jun	-12.06	94.3	22	84	1.8
2012	Jul	0.18	43.5	19	85	1.7
2012	Aug	19.04	51.1	20	78	1.9

2012	Sep	81.64	16.5	24	73	2.1
2012	Oct	-99.33	253.5	24	75	2.2
2012	Nov	27.14	231.7	24	81	1.9
2012	Dec	-17.29	377.4	23	79	1.9
2013	Jan	133.56	21.2	24	72	2.4
2013	Feb	132.92	160.4	26	64	2.2
2013	Mar	101.9	207	25	72	2.2
2013	Apr	283.96	171.9	24	81	1.8
2013	May	126.97	110.3	25	80	2.4
2013	Jun	-22.02	151.7	20	84	1.9
2013	Jul	115.54	31.8	19	81	1.9
2013	Aug	18.25	102.2	18	79	2.1
2013	Sep	-23.47	95.5	22	75	2
2013	Oct	100.6	208.6	24	72	2.3
2013	Nov	-12.14	301.3	22	78	1.9
2013	Dec	-75.7	77.4	22	79	1.8
2014	Jan	113.87	7	26	71	2.4
2014	Feb	19.59	0	25	69	2.2
2014	Mar	-9.4	121.8	24	73	2
2014	Apr	-14.32	355.69	23	76	2.2
2014	May	-30.16	392	21	79	2.5
2014	Jun	-28.48	156.2	18	81	2
2014	Jul	16.54	40.7	17	81	2
2014	Aug	-28.97	54.7	20	77	2.1
2014	Sep	37.68	19.2	20	75	2.2
2014	Oct	-104.26	198.6	23	77	2.3
2014	Nov	-138.298	632.8	22	77	2
2014	Dec	41.09	99.7	23	55	2
2015	Jan	137.34	173.2	24	59	2.3
2015	Feb	130.85	99.5	28	63	1.8
2015	Mar	180.32	63.9	26	76	2.3
2015	Apr	-167.46	467	25	81	1.8
2015	May	-142.63	300	23	77	2.1
2015	Jun	-13.21	87.9	20	78	1.7
2015	Jul	20.33	48	21	73	2.2
2015	Aug	3.58	45.7	19	68	2.3
2015	Sep	94.56	6.6	21	71	2.2
2015	Oct	-83.53	23.7	23	77	2.4
2015	Nov	-374.06	295.1	22	71	1.8
2015	Dec	-19.7	42.8	23	71	1.7
2016	Jan	-31.84	173.2	24	67	1.8
2016	Feb	19.63	99.5	26	58	1.9
2016	Mar	72.45	63.9	26	62	1.9
2016	Apr	-233.12	467	24	79	2
2016	May	-172.56	300	22	82	1.8
2016	Jun	-25.3	87.9	21	78	1.7
2016	Jul	41.84	2.3	21	79	1.9
2016	Aug	32.6	45.7	20	72	2.2

2016	Sep	76.8	6.6	22	71	2.2
2016	Oct	91.837	23.7	23	68	2.1
2016	Nov	-152.06	295.1	23	75	2.1
2016	Dec	71.57	42.8	24	69	1.9

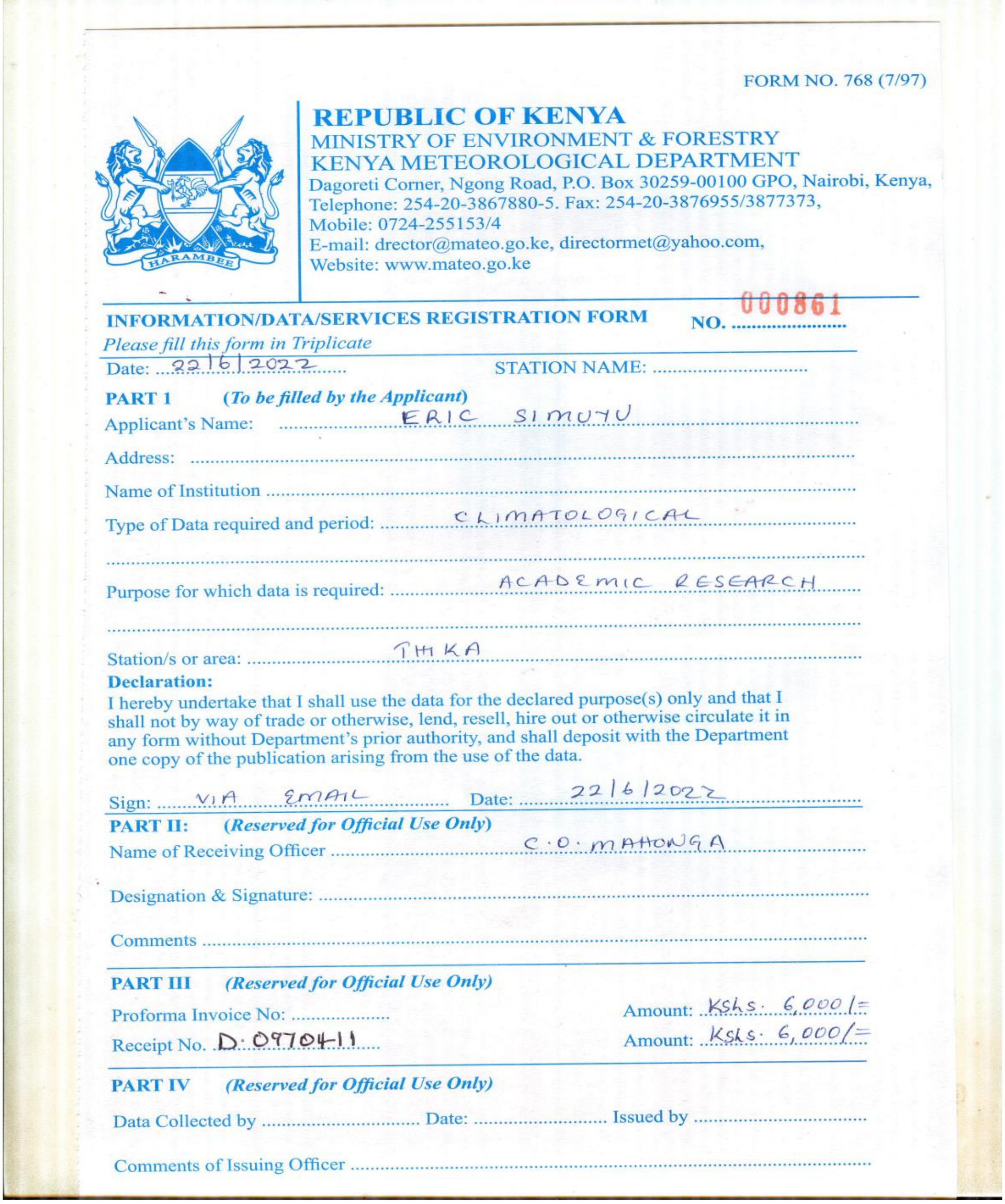
Appendix E: Thika dam Operational data

Year	Mon	Level(m)	Vol. (Mm^3)	Dam Discharge (m^3/s)	Year	Mon	Level(m)	Vol. (Mm^3)	Dam Discharge (m^3/s)
1997	1	2041	70	1.08	2007	1	1980	70	0
1997	2	2039	62.3	1.71	2007	2	2041	69.8	0.69
1997	3	2037	58.9	1.94	2007	3	2040	67.5	1.73
1997	4	2035	54.7	0.9	2007	4	2039	65.1	1.42
1997	5	2041	69	0.91	2007	5	2041	69.7	0.45
1997	6	2041	70	0.31	2007	6	2041	70	0
1997	7	2041	70	0.6	2007	7	2041	70	0.48
1997	8	2041	70	0.98	2007	8	2041	70	1.1
1997	9	2040	67.6	1.57	2007	9	2041	70	1.1
1997	10	2037	58.5	0.88	2007	10	2041	70	1.1
1997	11	2041	70	0	2007	11	2041	70	1.1
1997	12	2041	70	0	2007	12	2041	69.5	1.45
1998	1	2041	70	0	2008	1	2040	66.5	2.04
1998	2	2041	70	0	2008	2	2038	62.2	2.59
1998	3	2041	70	0	2008	3	2036	55.2	3
1998	4	2041	70	0.33	2008	4	2034	50.9	2.09
1998	5	2041	70	0.68	2008	5	2035	54.3	1.4
1998	6	2041	70	0.65	2008	6	2035	54.6	1.61
1998	7	2041	69	0.83	2008	7	2034	52.2	1.78
1998	8	2041	69	1.27	2008	8	2033	49.4	1.8
1998	9	2040	69	1.7	2008	9	2032	47.1	1.82
1998	10	2038	61.9	2.07	2008	10	2031	44.6	1.47
1998	11	2037	58.9	1.46	2008	11	2033	48.6	0.28
1998	12	2036	55.4	1.82	2008	12	2035	52.8	1.14
1999	1	2035	51.9	1.84	2009	1	2034	50.6	1.85
1999	2	2032	45.7	2.27	2009	2	2032	45.9	2.45
1999	3	2029	39.6	2.11	2009	3	2029	40	2.5
1999	4	2028	37.8	1.15	2009	4	2026	35	1.98
1999	5	2033	48.3	0	2009	5	2025	32.1	1.05
1999	6	2034	51.9	0.48	2009	6	2026	33.7	1
1999	7	2034	50.2	1.72	2009	7	2025	32.9	1
1999	8	2033	48.3	1.76	2009	8	2024	31.7	1
1999	9	2031	44.7	1.85	2009	9	2024	30.4	0.92
1999	10	2029	39.6	2.15	2009	10	2024	31.1	0.5
1999	11	2027	34.6	1.79	2009	11	2030	42.3	0
1999	12	2034	50.2	0	2009	12	2034	51	0
2000	1	2036	56.8	0.99	2010	1	2037	58.4	0
2000	2	2035	52	1.76	2010	2	2039	64.4	0
2000	3	2032	48.3	2.13	2010	3	2040	67.9	0
2000	4	2030	41.7	2.15	2010	4	2041	70	0
2000	5	2028	37.8	1.65	2010	5	2041	70	0
2000	6	2026	34.6	1.5	2010	6	2041	70	0
2000	7	2025	31.4	1.37	2010	7	2041	70	0.77

2000	8	2023	29.1	1.4	2010	8	2041	68.6	1.44
2000	9	2022	24.6	1.42	2010	9	2040	65.9	1.81
2000	10	2020	24	1.43	2010	10	2039	63.4	1.52
2000	11	2020	23.7	1.16	2010	11	2041	68.5	0.6
2000	12	2021	24.6	1.11	2010	12	2041	70	0.93
2001	1	2025	30.6	0	2011	1	2041	69.2	1.25
2001	2	2031	45.1	0.4	2011	2	2040	66.6	1.79
2001	3	2031	45.1	1.46	2011	3	2039	63	1.79
2001	4	2032	46.9	0.82	2011	4	2037	59.8	1.89
2001	5	2041	70	0	2011	5	1980	63	0.44
2001	6	2041	70	0.07	2011	6	2040	66.6	0.96
2001	7	2041	70	1.34	2011	7	2040	66.7	1.48
2001	8	2040	69.9	1.58	2011	8	2039	64.7	1.58
2001	9	2039	64	1.86	2011	9	2039	63	1.6
2001	10	2037	58.9	2.06	2011	10	2039	63.3	1
2001	11	2036	56	1.39	2011	11	2041	70	0
2001	12	2036	56	1.78	2011	12	2040	70	0
2002	1	2035	52.8	1.79	2012	1	2041	69.6	0.5
2002	2	2033	49.4	2.03	2012	2	2040	67	1.74
2002	3	2032	45.8	2.12	2012	3	2039	62.7	2.25
2002	4	2030	43.5	1.69	2012	4	2037	58.1	1.68
2002	5	2040	70	0	2012	5	2040	67.5	0.97
2002	6	2041	70	0.17	2012	6	2041	70	1.68
2002	7	2041	69.3	0.85	2012	7	2041	70	0.91
2002	8	2040	69.2	1.29	2012	8	2041	70	0.57
2002	9	2039	64	1.77	2012	9	2041	69.7	1.29
2002	10	2037	58.9	2.07	2012	10	2041	68.7	1.03
2002	11	2039	63	0.57	2012	11	2041	70	1.25
2002	12	2041	70	0.09	2012	12	2041	70	1.5
2003	1	2041	70	0.3	2013	1	2041	69.9	1.39
2003	2	2041	70	0.76	2013	2	2041	68.8	1.56
2003	3	2040	66.6	1.76	2013	3	2039	64.8	2.17
2003	4	2039	63.6	1.49	2013	4	2041	68.2	2
2003	5	2041	70	0	2013	5	2041	70	2.67
2003	6	2041	70	0	2013	6	2041	69.8	1.17
2003	7	2041	70	0.08	2013	7	2040	67.9	1.83
2003	8	2041	70	0.89	2013	8	2039	64.4	2.08
2003	9	2041	69	1.34	2013	9	2037	59.6	2.26
2003	10	2040	66.6	1.91	2013	10	2035	54.8	2.41
2003	11	2041	68.3	0.88	2013	11	2034	51.1	1.87
2003	12	2041	70	0.96	2013	12	2035	53.5	0.59
2004	1	2041	69	1.58	2014	1	2037	59	1.11
2004	2	2040	66.6	1.81	2014	2	2036	56.7	2.02
2004	3	2038	62.4	2.17	2014	3	2035	53.7	1.63
2004	4	2039	70	0.8	2014	4	2035	53.2	1.15
2004	5	2041	70	0	2014	5	2037	58	0.86
2004	6	2041	70	0.38	2014	6	8767	63.3	0.81
2004	7	2041	69	1.28	2014	7	2040	66.2	1.4

2004	8	2039	67	1.89	2014	8	2039	64.3	2.25
2004	9	2037	59.9	1.95	2014	9	2038	61.8	2.45
2004	10	2036	54.9	2.08	2014	10	2037	59.2	2.1
2004	11	2038	59.9	0.57	2014	11	2039	62.8	0.63
2004	12	2040	66.4	1.4	2014	12	2041	69.8	0.59
2005	1	2040	65.8	1.5	2015	1	8557	67.5	2.25
2005	2	2039	63.7	1.71	2015	2	2038	61.4	3.11
2005	3	2037	59.2	2.05	2015	3	2646	53.5	3.35
2005	4	2037	58.1	0.64	2015	4	2032	47.4	2.54
2005	5	2040	65.8	0	2015	5	2036	57.3	0.28
2005	6	2041	70	0	2015	6	2041	69.8	0
2005	7	2041	70	0.37	2015	7	2041	69.3	1.35
2005	8	2041	70	1.03	2015	8	2040	66.5	2.38
2005	9	2041	69.8	1.33	2015	9	2038	60.7	2.86
2005	10	2040	66.9	1.89	2015	10	2035	53.7	2.93
2005	11	2039	64.7	1.9	2015	11	2036	56.6	1.02
2005	12	2039	62.7	1.84	2015	12	2041	69.3	0.02
2006	1	2037	59.3	2.09	2016	1	2040	69.7	1.35
2006	2	2035	53.8	2.47	2016	2	2041	68.9	1.37
2006	3	2033	48.4	2.4	2016	3	2634	66.1	2.35
2006	4	2031	44.7	1.4	2016	4	2634	66.1	2.35
2006	5	2037	60.8	0	2016	5	2041	69.7	2.2
2006	6	2041	70	0.48	2016	6	2655	69.9	1.03
2006	7	2041	68.6	1.69	2016	7	2040	67.5	2.44
2006	8	2039	63.7	2	2016	8	2038	61.8	3.03
2006	9	2038	60.8	2.22	2016	9	2035	54.6	3.16
2006	10	2036	55.9	2.49	2016	10	2032	47.2	3.15
2006	11	2035	54.1	1.47	2016	11	2029	39.3	2.97
2006	12	2041	69.5	1.47	2016	12	1968	34.6	2.85

Appendix F: KMD Data requisition invoice



FORM NO. 768 (7/97)

REPUBLIC OF KENYA
MINISTRY OF ENVIRONMENT & FORESTRY
KENYA METEOROLOGICAL DEPARTMENT
Dagoreti Corner, Ngong Road, P.O. Box 30259-00100 GPO, Nairobi, Kenya,
Telephone: 254-20-3867880-5. Fax: 254-20-3876955/3877373,
Mobile: 0724-255153/4
E-mail: drector@mateo.go.ke, directormet@yahoo.com,
Website: www.mateo.go.ke

INFORMATION/DATA/SERVICES REGISTRATION FORM **NO.** 000861

Please fill this form in Triplicate

Date: 22/6/2022 STATION NAME: ....

PART 1 ***(To be filled by the Applicant)***

Applicant's Name: ERIC SIMUYU

Address: ....

Name of Institution ....

Type of Data required and period: CLIMATOLOGICAL

....

Purpose for which data is required: ACADEMIC RESEARCH

....

Station/s or area: THIKA

Declaration:

I hereby undertake that I shall use the data for the declared purpose(s) only and that I shall not by way of trade or otherwise, lend, resell, hire out or otherwise circulate it in any form without Department's prior authority, and shall deposit with the Department one copy of the publication arising from the use of the data.

Sign: VIA EMAIL Date: 22/6/2022

PART II: ***(Reserved for Official Use Only)***

Name of Receiving Officer C.O. MAHONGA

Designation & Signature: ....

Comments ....

PART III ***(Reserved for Official Use Only)***

Proforma Invoice No: .... Amount: Kshs. 6,000/=

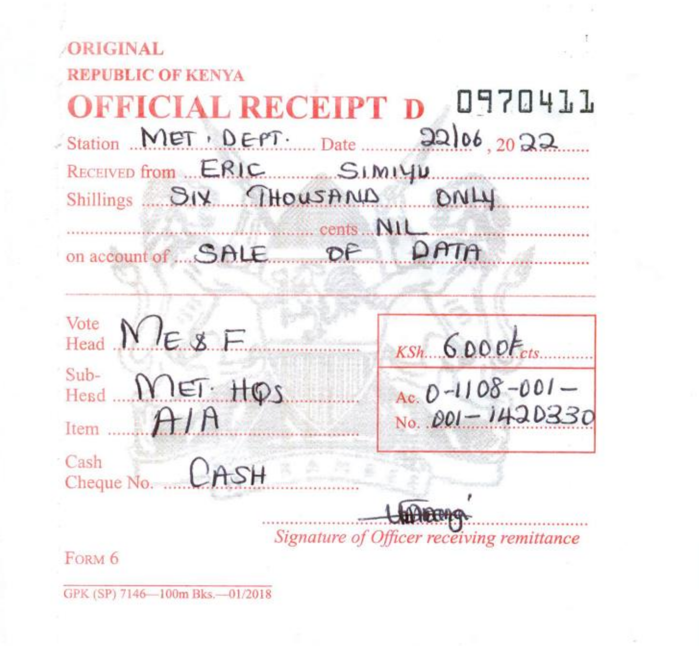
Receipt No. D.0970411 Amount: Kshs. 6,000/=

PART IV ***(Reserved for Official Use Only)***

Data Collected by .... Date: .... Issued by ....

Comments of Issuing Officer ....

Appendix G: KMD payment for data receipt



ORIGINAL

REPUBLIC OF KENYA

OFFICIAL RECEIPT D 0970411

Station MET. DEPT. Date 22/06, 2022

RECEIVED from ERIC SIMIYU

Shillings SIX THOUSAND ONLY

cents NIL

on account of SALE OF DATA

Vote Head ME & F	KSh. 6000/- cts.
Sub-Head MET. HQS	Ac. No. 0-1108-001-001-1420330
Item A/A	
Cash Cheque No. CASH	

Signature of Officer receiving remittance

FORM 6

GPK (SP) 7146—100m Bks.—01/2018

Appendix H: NCWSC research data approval

NAIROBI WATER
Improving Reliability

NAIROBI CITY WATER & SEWERAGE COMPANY LTD.
KAMPALA RD, P. O. Box 30656-00100, Nairobi, Kenya
Tel: +254 0703 080 000
Email: info@nairobiwater.co.ke
www.nairobiwater.co.ke

NCWSC/HR/TRG.14/Vol.8/09/MMM/ak 12th March,2020

Eric Simiyu Juma
Moi University
P.O Box 3900-,
Eldoret
Cell: 0714697231

Dear Eric,

RE: RESEARCH PROJECT

Reference is made to your letter dated 24th January, 2020 on the above mentioned subject.

Approval is hereby granted for you to collect data on **23rd. 24th, 25th,26th** and **27th March, 2020** for your degree project titled ***"Modelling the impact of non- revenue water, population growth and improved living standard on unmet water demand using weap model –the case study of Nairobi City.*** "at the Nairobi City Water and Sewerage Company(NCWSC) in Nairobi City County.

The Non- Revenue Water Manager whose office is located at National Water offices, Dunga road will assist you with the relevant Data/information in relation to your research.

All findings/information on Company matters should be accorded utmost confidentiality.

Please note upon completion, you will be expected to submit a report to the mentioned officer for onward submission to the office of the undersigned.

By a copy of this letter the following Officers are hereby informed accordingly.

i. Non-Revenue Water Manager-National Water offices, Dunga road
ii. Research and Development Manager

Yours Sincerely,

Eng. Nahason Muguna
Ag. Managing Director

Appendix I: Plagiarism Certificate

SR251

ISO 9001:2019 Certified Institution

EDU 999 THESIS WRITING COURSE

PLAGIARISM AWARENESS CERTIFICATE

This certificate is awarded to

ERIC SIMIYU JUMA

TEC/PGCS/01/14

In recognition for passing the University's plagiarism

Awareness test for thesis: **MODELLING THE IMPACT OF VARIOUS FUTURE SCENARIOS ON UNMET WATER DEMAND USING WATER EVALUATION AND PLANNING MODEL** with a similarity index of 11% and striving to maintain academic integrity.

Awarded by:

Prof. Anne Syomwene Kisilu
CERM-ESA Project Leader Date: 21/08/2023