Developing a sustainable water management plan for Ruiru, Thiririka and Ndarugu subbasins in Kenya using WEAP

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

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DEDICATION

Dedicated to my wife Felista Kisavi and my child Gloria Kahaso for their perseverance, prayers and support during the entire study period.

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ABBREVIATIONS

AIDS	Acquired Immune Deficiency Syndrome
ASCE	American Society of Civil Engineers
BBM	Building Block Method
BCM	Billion cubic meters
BOD	Biochemical Oxygen Demand
CBS	Central Bureau of Statistics
CCME	Canadian Council of Ministers of the Environment
Cu	Copper
^{O}C	Degree Celsius
DRIFT	Downstream Response to Imposed Flow

	Transformation
DSS	Decision Support System
EC	Electrical Conductivity
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization
GIS	Geographical Information System
GOK	Government of Kenya
GPS	Geographical Positioning System
HEC – HMS	The Hydrologic Engineering Center's Hydrologic Modeling System
IFIM	Instream Flow Incremental Methodology
IHA	Indicators of Hydrologic Alteration
ILRI	International Livestock Research Institute
IUCN	International Union for Conservation of Nature and Natural Resources
IWRM	Integrated Water Resources Management
JICA	Japanese International Corporation Agency
$\mathbf{K_c}$	Crop coefficient
LH	Lower Highland zones
MCM	Million Cubic Metres
$\mathbf{m^3/d}$	Cubic meters per day

MENR	Ministry of Environment and Natural Resources
mg/l	milligram per liter of water
MJ	Mega Joule
ML	Million liters
MWI	Ministry of Water and Irrigation
M^2	square meter
NTU	Nephelometric Turbidity Units
NWMP	National Water Master Plan
PHABSIM	Physical Habitat Simulation Model
R^2	Coefficient of Determination
REALM	Resources Allocation Model
SEI	Stockholm Environmental Institute
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
UH	Upper Highland zones
UM	Upper Midland zones
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USDA	United States of America Department of Agriculture
USGS	United States Geological Survey
WASAM	Water Allocation Scheduling and Monitoring
WEAP	Water Evaluation and Planning Systems Model

WCED	World Commission on Environment and Development
WRMA	Water Resources Management Authority
VB –WAS	Volta Basin Water Allocation System

ABSTRACT

Ruiru, Thiririka and Ndarugu Sub-Basins have been subjected to intensive agricultural, industrial activity and population pressure. The growing demand over a limited endowment of water has generated competition between upstream and downstream users and is causing conflicts over its use. The increased competition for water is putting great pressure on the local hydrology and ecosystem. The increase in population in Juja, Jomo Kenyatta University of Agriculture and Technology, Gatundu, Ruiru and Nairobi and the increasing economic activities have increased the demand for water for

domestic use, food security and industrial development. Two dams have been proposed by the Government for construction along Ndarugu and Ruiru rivers to supply water to Nairobi. With all these competing water demands, there is need to develop strategies for sustainable water resources management in the basin. The study utilizes the water allocating model, WEAP, in simulating and predicting the effect of water allocation scenarios and possible management options. The drainage area for Ndarugu, Thiririka and Ruiru sub-basins are $395km^2$, $328km^2$ and $476km^2$ respectively.

The data that was used in the study were collected from the Ministry of Water and Irrigation, Water Resources Management Authority Regional offices in Machakos and Kiambu, Central Bureau of Statistics, Meteorological Department in Nairobi and Agricultural Offices in Thika and Ruiru. This data include population, discharge, agriculture, rainfall and other climatic data. The Global Positioning System (GPS) was used to determine the co-ordinates and altitudes of towns, institutions, farms and point pollution. Water samples were collected from the upstream of the three rivers in Gatundu and Githunguri area and downstream of the three rivers at Kalimoni primary school and Juja farm. The water samples were collected during the dry season in August, 2009 and in January, 2010. The water quality parameters that were analyzed were Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Electrical Conductivity (EC), Chloride (Cl), Turbidity and Copper (Cu). The WEAP model was used to simulate water use in urban, agriculture, institution and industries sectors over a period set to 1980 to 2008 of varying rainfall and river flows. Calibration and validation was done by comparing the simulated and measured flows for stream flow gauges located at 3CB05, 3BD05 and 3BC12. The crop coefficient and reference evapotranspiration values used on the study were varied until an acceptable value of correlation coefficient (R^2) was achieved. The correlation coefficient (R^2) between the simulated and observed monthly stream flow was assessed for the three gauging stations. For station 3BC12, an R^2 of 0.803 was obtained during calibration and 0.811 during validation. The coefficient of correlation for station 3CB05 was 0.801 during calibration and 0.804 during validation. For station 3BD05, the R^2 of 0.849 was achieved during calibration and 0.88 during validation.

Four water plan strategies were identified and tested for their effectiveness in meeting future water demand through the WEAP model. The strategies are: Urban water use efficiency, surface storage, conjunctive management and groundwater storage and land use planning and management. The results indicate that by combining the four strategies that were identified, it is possible that all the water demand in the subbasin could be met.

From the study, the high value of correlation coefficient (R^2 of 0.849 and 0.88) between simulated and observed flow for model calibration and validation respectively at 3BD05 gauging station implies an acceptable performance of the WEAP model in stream flow generation in Ruiru and Ndarugu basin. The model could therefore be used to predict water demand and supply for future scenarios for Ruiru, Thirirka and Ndarugu sub-basins. The projections of the water demand by the WEAP model in the study area indicates that it will grow from 75.1 MCM in 2010 to 96.3 MCM and 129.2 MCM in 2020 and 2030 respectively. The proposed reservoirs under the surface water strategy should be constructed to meet the current and future water demand.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Introduction

Fresh water is a finite and vulnerable resource, essential to sustain life, economic development and the environment. The world's freshwater resources are under increasing pressure; so, many still lack access to adequate water supply for basic needs. Growth in population, increased economic activity and improved standards of living lead to increased competition for, and conflicts over the limited freshwater resource.

Current estimates indicate that the total volume of water on earth is about 1.4×10^9 km^3 of which about 97% is in the seas or oceans and therefore saline, 77% of freshwater is locked up in icecaps and glaciers, leaving negligible percentage in easily accessible sources like lakes and rivers (USGS, 2008). Water withdrawals have increased more than twice as fast as population growth and currently one third of the world population live in countries that experience medium to high water stress (Development, 2008).

Water resources all over the world are under increasing pressure from the continuous growing demand for sufficient quantities of good quality water for all purposes. As pointed out in the World Water Vision (Cosgrove and Rijsberman, 2000): This increase in water withdrawals implies that water stress will increase significantly in 60% of the world, including parts of Africa, Asia and Latin America. Global consumption of water is doubling every 20 years more than twice the rate of human population growth.

According to the United Nations (IFG, 2001), more than one billion people on earth already lack access to fresh drinking water. If the current trends persist, by 2025 the demand for freshwater will rise by 56 percent and as many as two-thirds of the world population will be living with serious water shortages or absolute water scarcity.

Kenya is a water scarce country with renewable fresh water per capita of 647 m^3 against the United Nations recommended minimum of 1000 m^3 (JICA, 1992). Projections indicated that if no remedial measures are taken then the per capita water availability will decline to $235m^3$ by 2025 which is considered to be below limits of water barrier (GOK, 2009a). The World Water Development Report (UNESCO, 2006) sums up the current situation in Kenya as: 'Demand management strategies are lacking, and water resources allocation decisions related to surface and groundwater abstractions are made without data.' With a population of 38.6 million in 2009 and a projected population of 43 million by 2015 (MWI, 2007), Kenya faces enormous challenges in the management of its limited water resources. Despite a remarkable decrease in population growth rate over the past decades, Kenya's annual population growth rate is still one the highest in the world at 2.6%. Population growth rates in densely populated regions have led to rural – urban migration. This has over-stretched resources in the urban areas. Decreasing standards of land management, infrastructure, water and sanitation and municipal services have led to a steady decline on health and environmental standards as well as increased vulnerability to human-made and natural disaster. The rate of urbanization in Kenya is one of the highest in the world. While the estimated annual rate of growth of urban population in Kenya is 7.05% for the period of 1995 – 2007, the average for African cities is 4.37% and 2.57% for the world (GOK, 2009b). Kenya's Vision 2030 (GOK, 2007) recognizes the crucial role water resources will play in supporting the socio-economic development of Kenya. The Vision aims at ensuring that all Kenyans have access to adequate water resources and sanitation facilities by 2030 and this would be achieved through implementing programmes and projects on water resources management, water storage and harvesting, water supply and sanitation and irrigation and drainage. Vision 2030 recognizes that water is a basic need and an important catalyst for both economic and social development of the country. It states that "access to water for human consumption, agriculture, and livestock use is a major problem in rural areas." It is thus paramount to improve the living standards of the rural communities through the provision of sustainable water resources which will be used productively.

Athi River Catchment has the lowest volume of surface water resources (21.3 x 10^3 m^3 /year/km^2) (MENR, 2002) and 162 m^3 per capita amongst the main Kenyan catchments. Ruiru, Thiririka and Ndarugu sub-basins, which are parts of the Athi River Catchment, have a total area of 1199 km^2. The main tributaries of Ndarugu River are Ruabora, Karakuta and Githobokoni. The tributaries for Ruiru River are Makuyu, Kamathai and Gathamayu. The tributary for Thiririka River is Theta. The main activities in the catchment are tea, coffee and flower farming.

Past studies that have been carried out in Ruiru and Ndarugu sub-basins focused on evaluating the performance of a monthly water balance in Ndarugu and comparison of run-off response of two sub-basins in the upper Athi Basin (Nyadawa and Kamau, 2001; Nyadawa and Muiruri, 2001). However, no study has been carried out on modeling of water supply and demand in Ruiru, Thiririka and Ndarugu sub-basins considering the increasing water demand in the basins and its effects on the river flow. The Gatundu South Water Supply and Sanitation Company intends to enhance domestic water supply to its supply area by constructing a reservoir with provisions to abstract 1000 m^3 per day from Theta River (Kibson, 2009). Ruiru and Juja Water and Sewerage Company is constructing a retention weir along Ruiru River to boost its water supply. This research was analyzing the water demands, supply and water quality in Ruiru, Thiririka and Ndarugu Sub-Basins. Simulations and analysis of various water allocation scenarios were used to predict the outcome of future water demands of the basins.

1.2 Problem Statement

The challenges in Ruiru, Thiririka and Ndarugu sub-basins include severe water scarcity, underdevelopment of renewable freshwater resources, climate variability, catchment degradation, water resources degradation and competing needs targeting scarce water resources (GOK, 2008). Ruiru, Thiririka and Ndarugu Basins (sub-basins of Athi River Basin) have been subjected to intensive agricultural, industrial activity and population pressure. The growing demand over a limited endowment of water has generated competition between upstream and downstream users and is causing conflicts over its use. The increased competition for water is putting great pressure on the local hydrology and ecosystem. There is the danger of drying up of Ndarugu, Thiririka and Ruiru Rivers during the dry season as evidenced by low flows during the month of February (Figure A.1.1, Figure A.1.2 and Figure A.1.3). The increase in population in Juja, Jomo Kenyatta University, Gatundu, Ruiru and Nairobi and the increasing economic activities have increased the demand for water for domestic use, food security and industrial development. Already, two dams have been proposed for construction along Ndarugu and Ruiru rivers to supply water to Nairobi (JICA, 1992).

Due to varying activities along Ruiru, Thiririka and Ndarugu Sub-Basins, environmental degradation and water pollution has been experienced in the catchment. Ndarugu River is heavily polluted by quarry mining next to the river near Juja Water and Sewerage Company intake works along Nairobi – Thika highway (Figure A.2.1). Pollution in Ndarugu River is especially high during coffee pulping especially in the parts of Gatundu where effluent is discharged directly into the river. (Figure A.3.1). Ruiru River is also polluted by quarrying activities along the river (Figure A.2.2) and sewage disposal from Ruiru town.

1.3 Objectives

1.3.1 Major Objective

The main objective of the research was to model water use in Ruiru, Thiririka and Ndarugu sub-basins taking into account the growing demand and diversification.

1.3.2 Specific Objectives

1. To document major water demands and point pollution in Ruiru, Thiririka and Ndarugu sub-basins.
2. To calibrate and validate WEAP model as a tool for water allocation in Ruiru, Thiririka and Ndarugu sub-basins.
3. To simulate effect of future water use change scenarios in Ruiru, Thiririka and Ndarugu sub-basins and propose water use management strategy.

1.4 Justification

Kenya's fresh water per capita has been declining and projected to reach 235 m^3 by 2025 unless effective measures to address the challenges are implemented. Efficient water management will, therefore, not only contribute to sustainable long term economic growth but also to poverty reduction, health and security (GOK, 2007). The unsustainable use of the river water and the increasing population may lead to social conflicts, environmental degradation and threaten the existence of Ruiru, Thiririka and Ndarugu Rivers.

Sustainable management strategies have been defined by many groups, such as the "Bruntland Commission," as those that meet the needs of the present without compromising the ability of future generations to meet their own needs. The essential needs of the poor should be given priority and limitations are imposed by technology and social organization on the ability of the environment to meet present and future needs (WCED, 1987). The joint UNESCO/ASCE committee on Sustainable Water Use

Strategies (Loucks et al., 1996) has defined sustainable water resource systems as those that fully contribute to the needs of society, now and in the indefinite future, while protecting their cultural, ecological, and hydrological integrity.

Due to the growing water demand over a limited water resource, resulting into competition and conflicts over water use, there was need for a study to address the following questions concerning Ruiru, Thiririka and Ndarugu sub-basins:

- What is the current and future water demand in the sub-basins?
- How can the proposed reservoirs in Ruiru and Ndarugu Rivers be used to meet the water demand in Ruiru and Ndarugu sub-basins and its environs of Nairobi?
- How can an environmental flow requirement apportioned for the environment affect water supply in the basin?
- What alternative strategies are there to increase water supply in the basin?

1.5 Description of the Study Area

1.5.1 Location

Ruiru, Thiririka and Ndarugu Sub-Basins are located in the Central part of Kenya (Figure 1.1). The three sub-basins are located in the upstream of Athi River Basin (Figure 1.2) between latitude 0^0 50' 6''S and 1^0 11'42''S and between longitudes 36^0 35'2''E and 37^0 10'40''E. The drainage area is coded by the Government of Kenya as 3C and 3B (sub catchments in Athi Basin) and drains Ndarugu, Ruiru and Thiririka Rivers which are tributaries of Athi River. Ndarugu sub-catchment extends from Kieni and Kinale forest eastwards and parts of the ridges of Aberdares to Juja farm all the way to Munyu where it is joined by River Komu before it joins Athi River.

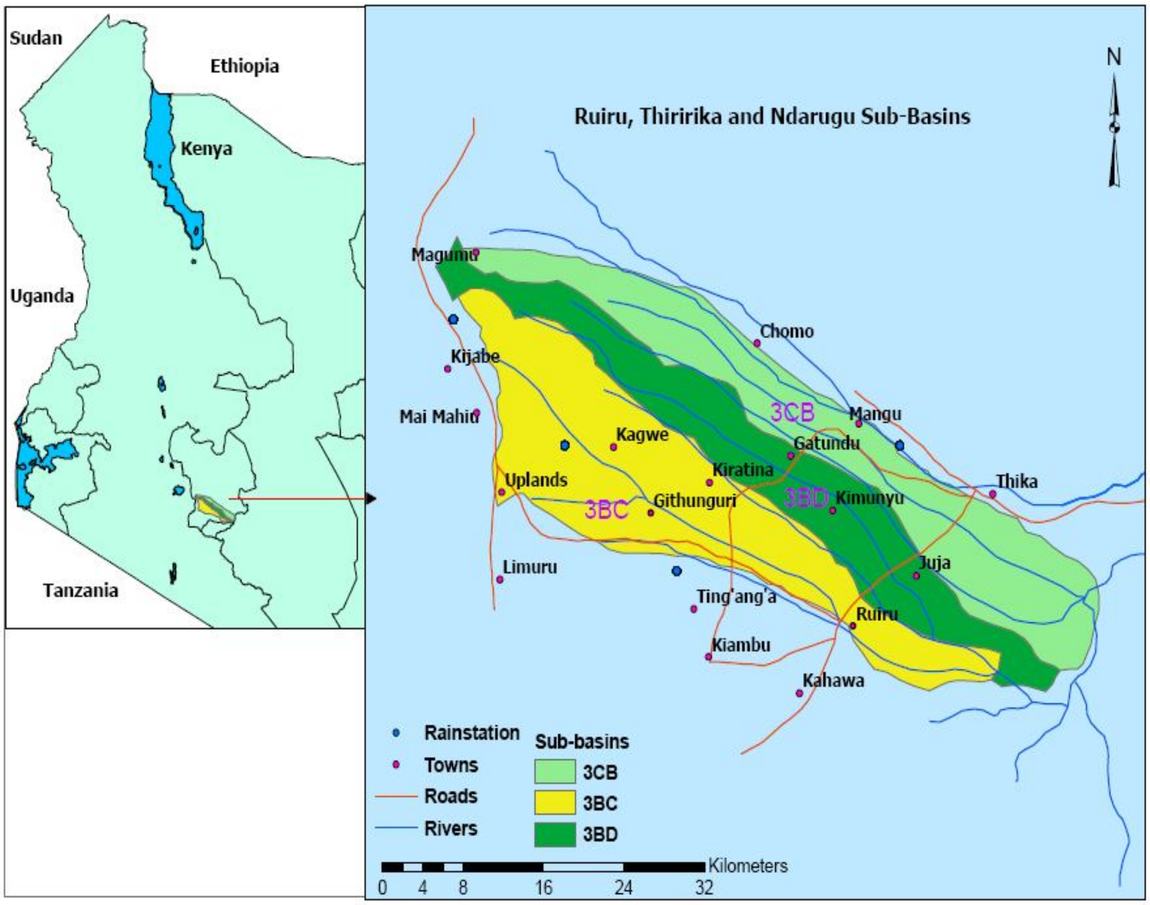

Figure 1.1 Locations of Ruiru, Thiririka and Ndarugu Sub-Basins

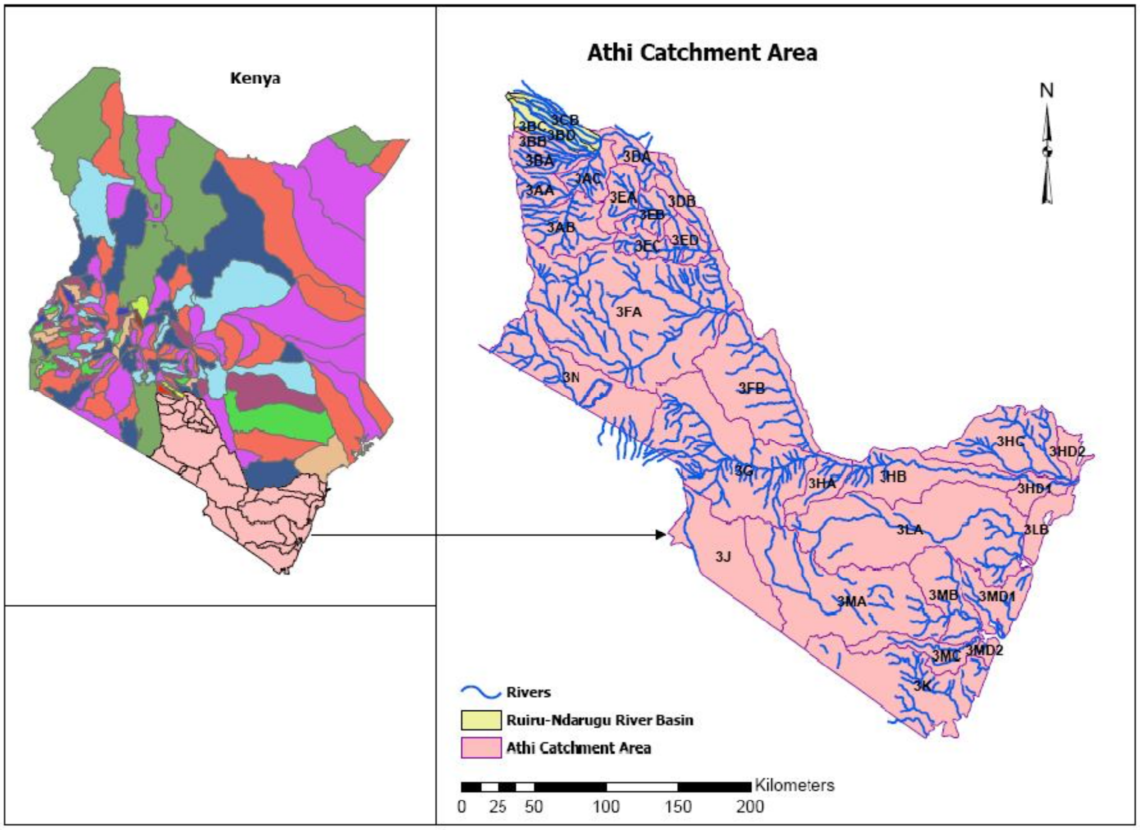

Figure 1.2 Athi Catchment (Source: ILRI, 2008)

The sub-catchment covers wholly or partially several locations in both Thika and Kiambu districts (Figure 1.3) namely Juja, Gatundu, Kamwangi, Kanyoni among many others in line.

The basin is divided into 3 sub watersheds according to the river gauging stations designations (GOK, 1992) namely 3BC, 3CB and 3BD (Figure 1.4). River Ndarugu is a perennial river with its source in the Kikuyu escarpments. It meanders through farmed slopes of Gatundu and Thika District before joining Athi River at Munyu near Kilimambogo. The tributaries of Ndarugu River are Ruabora, Githobokoni and

Karakuta rivers. Ruiru and Thiririka rivers also originate from Kikuyu escarpment and pass through Kiambu and Gatundu Districts and later join Athi River. The tributary for Thiririka River is Theta River.

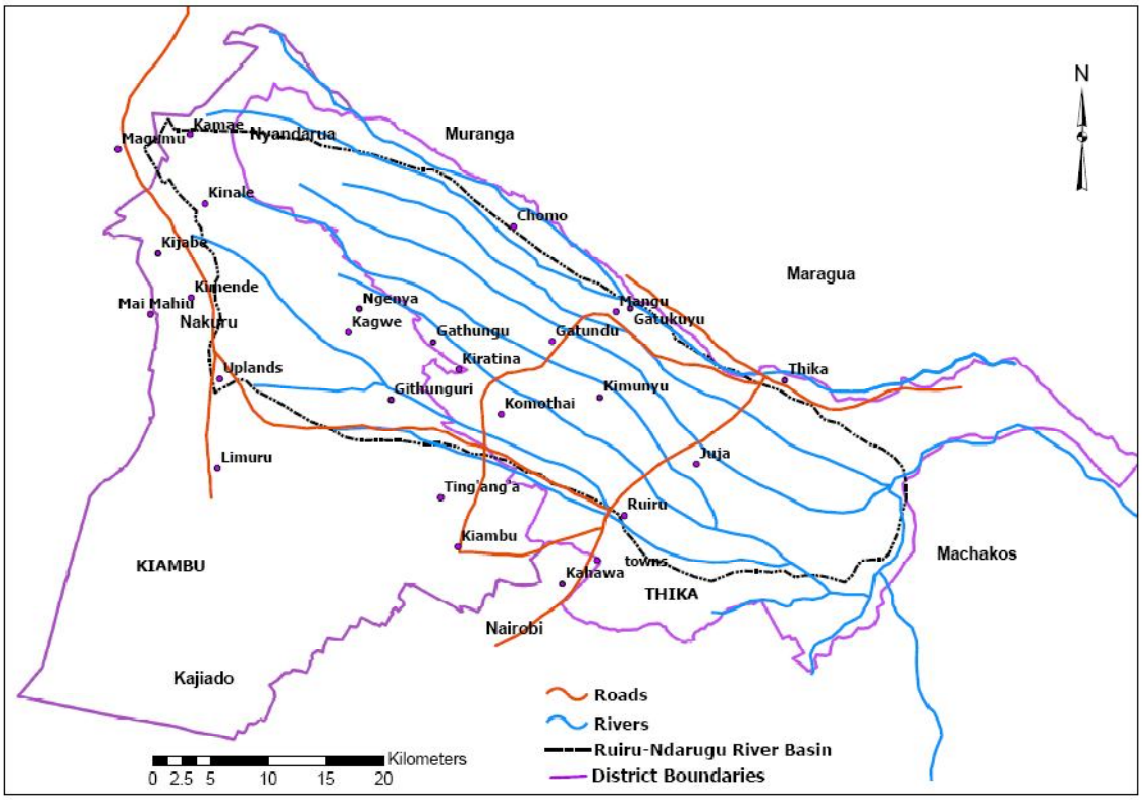

Figure 1.3 Ruiru, Thiririka and Ndarugu Sub-Basin District Boundaries

The Theta River sub catchment lies within the humid to sub-humid agro-climatic zones of central Kenya. The upper sub-catchment which is within the Kikuyu Escarpment forest comprises the humid zone and is the source of Theta and its tributaries namely Kiragi and Thaara streams. The tributaries for Ruiru River are Makuyu, Kamathai and

Gathamayu rivers. Other tributaries for Ruiru river that are feeding Ruiru dam are Kanyiriri, Kimaiti, Waingere, Ngeteti, Kamiditi, Kibathithi and Kibethithi rivers.

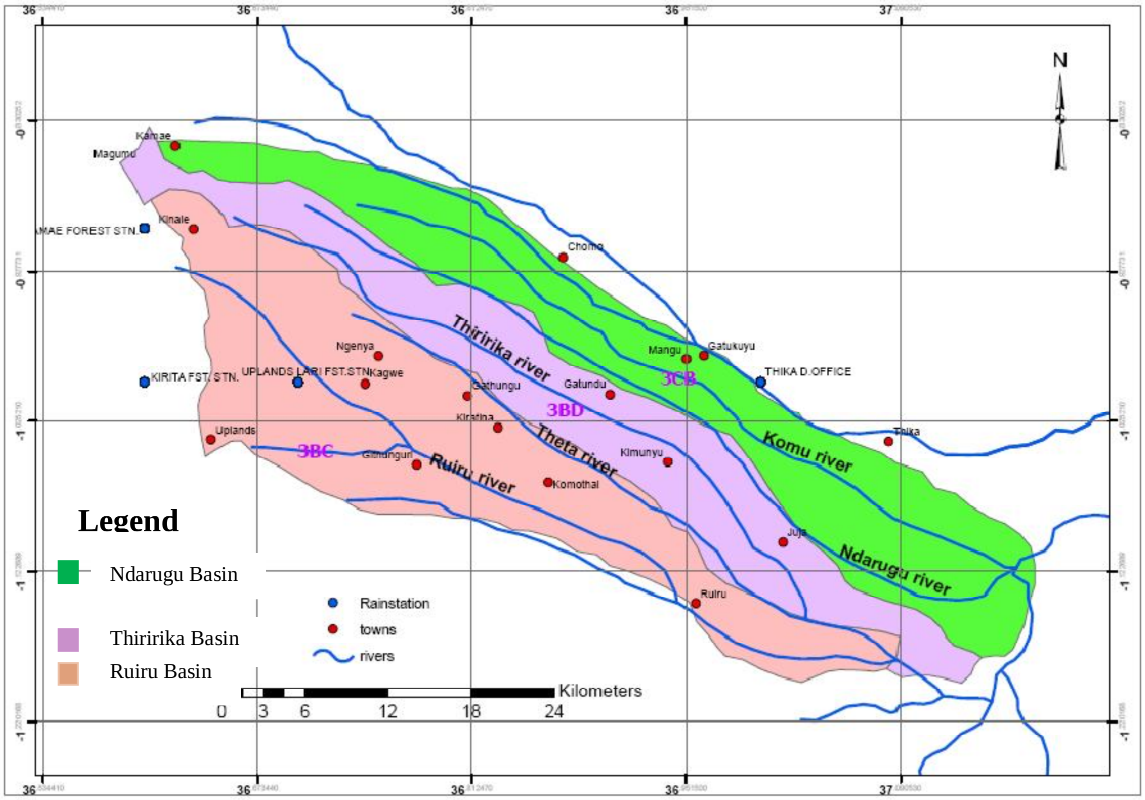

Figure 1.4 Ruiru, Thiririka and Ndarugu Basin Sub-Watershed

1.5.2 Climate

The study area is located in a two rainfall season zone (April to May and October to December). The mean annual rainfall for Ndarugu, Ruiru and Thiririka Sub-Basins are 1126 mm, 1118mm and 1195 mm respectively. Rainfall is largely influenced by altitude (Figure 1.5). The long rainy season is from March – May while the short rainy season is from October - November with peaks in April and November respectively. The average annual rainfall increases from less than 600 mm in the low eastern plains to more than 2000 mm on the southeastern windward side of the Nyandarua range.

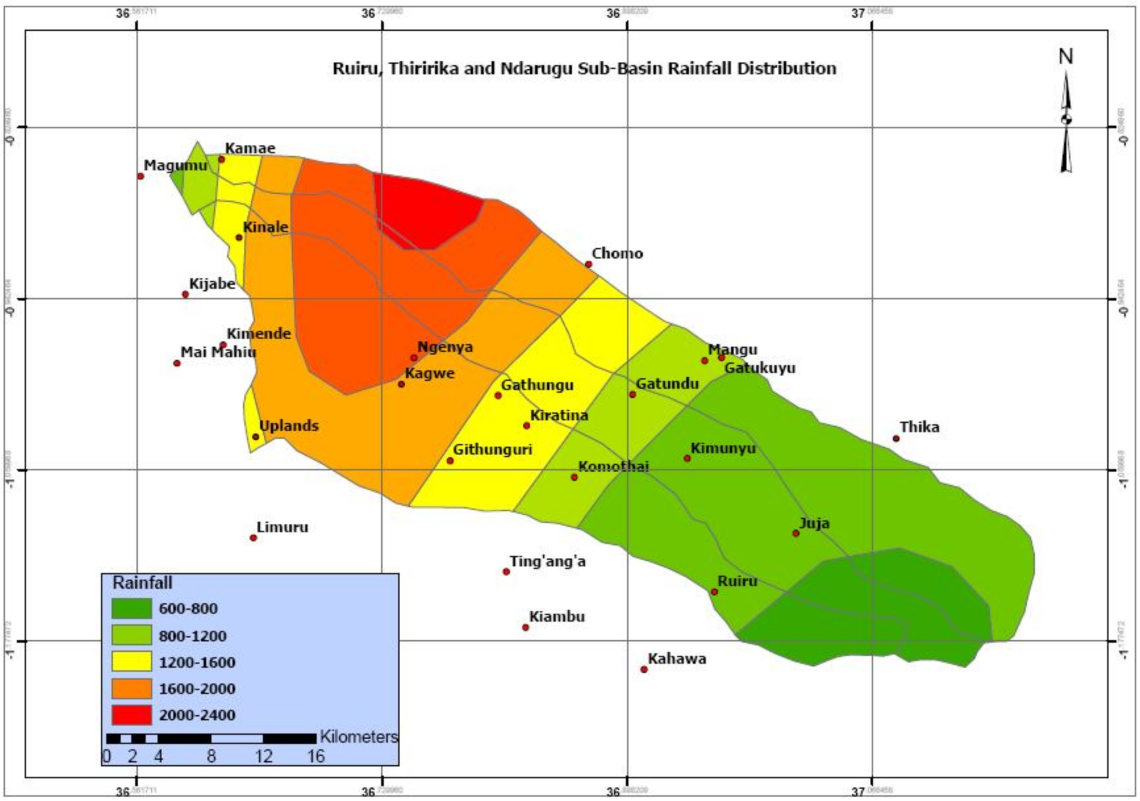

Figure 1.5 Ruiru, Thiririka and Ndarugu Sub-Basin Rainfall Distribution

(Source: ILRI, 2008)

The mean annual temperature in the forest zone (Figure 1.8) is 12.9 ℃ with a mean maximum temperature of 18.3^{o}C. The mean minimum temperature in this region is 7.5^{o}C. In the main coffee zone, the mean annual temperature is 19^{o}C with a mean maximum temperature of 25.1^{o}C. The mean minimum temperature in this region is 13.0^{o}C.

1.5.3 Geology and Soils

The Nyandarua Range influences the physiography of the Greater Kiambu district. The central landscape is dominated by undulating to rolling topography as well as high elevations (volcanic foothill ridges). The soils of this area are moderately to highly fertile. On the mountains, soils developed on olivine basalts and ashes of major older volcanoes are found. They may be shallow or leached and very acidic. Soils of the hills are generally variably fertile and can only be found in the western part of the district. Fertile upland soils occur in the western part, others of moderate to low fertility in the eastern part of Kiambu district (Figure 1.6). East of Ruiru, the plateaus have soils of variable fertility. On the lower topographical sites, soils, which have developed on alluvium, are found. They are moderate to highly fertile. Dominant soil types in the districts of Kiambu and Thika are humic Andosols and Nitosols; which were developed from pyroclastic rocks during the tertiary period (MOA, 2006).

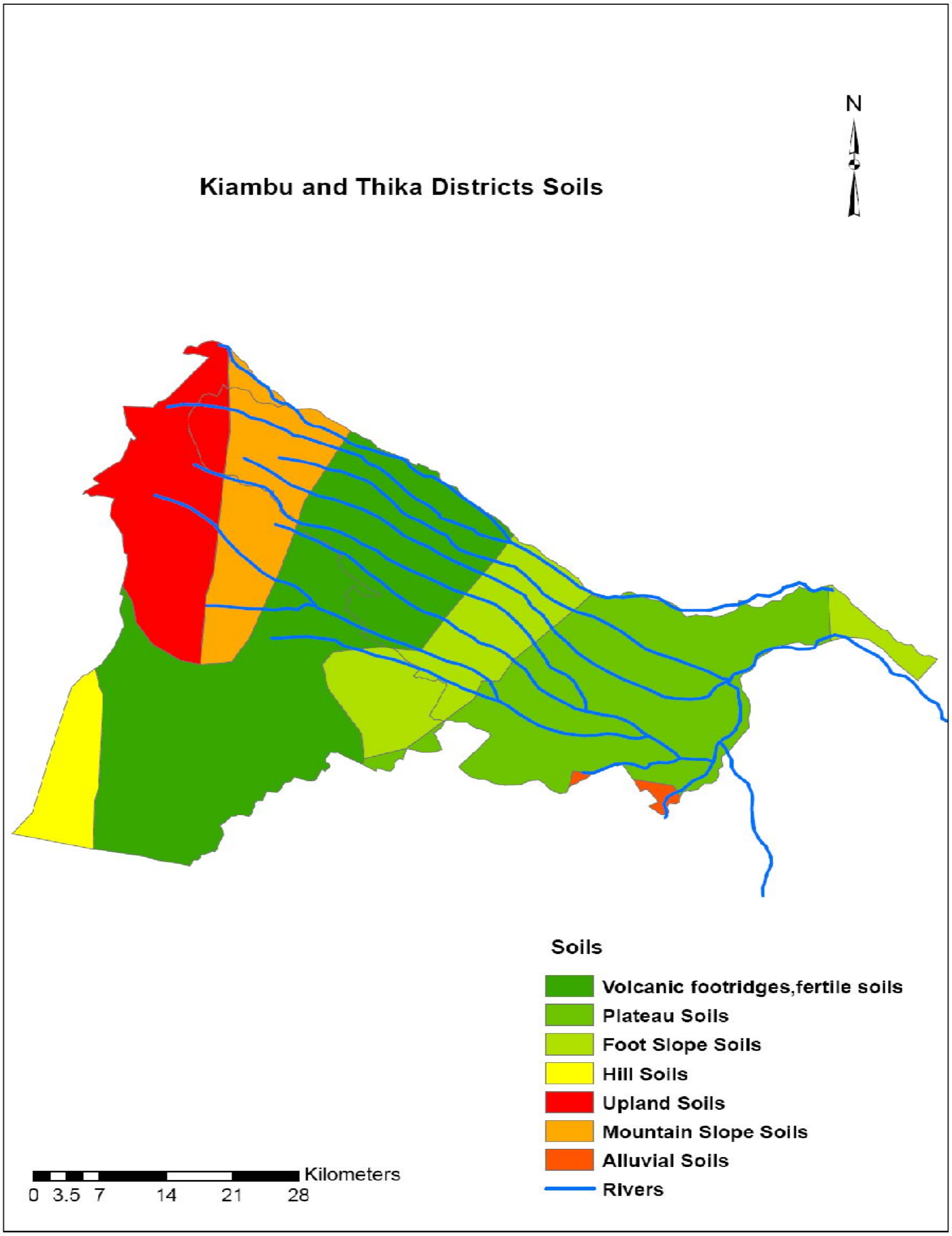

Figure 1.6 Soils for Kiambu and Thika districts (Source: MOA, 2006)

1.5.4 Agro-Ecological Zones and Land Use

The major agro-ecological zones in the basin are Forest Zone (UH0), Tea-Dairy Zone (LH1), Coffee-Tea Zone (UM1), Main Coffee Zone (UM2), Marginal Coffee (UM3), Maize and Marginal Cotton (UM4), and Ranch Zone (UM5) as shown in Figure 1.8.The current actual land use involves the growing of cash crops, food crops, vegetables and fruits (Figure 1.7). The cash crops are tea, coffee, avocados, pineapples and macadamia. The vegetables are kales, cabbages and spinach. The fruits are bananas, pineapples and avocados. The food crops are maize, beans, Irish potatoes, arrow roots and sweet potatoes. Pure and improved crosses of dairy cattle, mainly put under zero grazing, dominate livestock keeping enterprises.

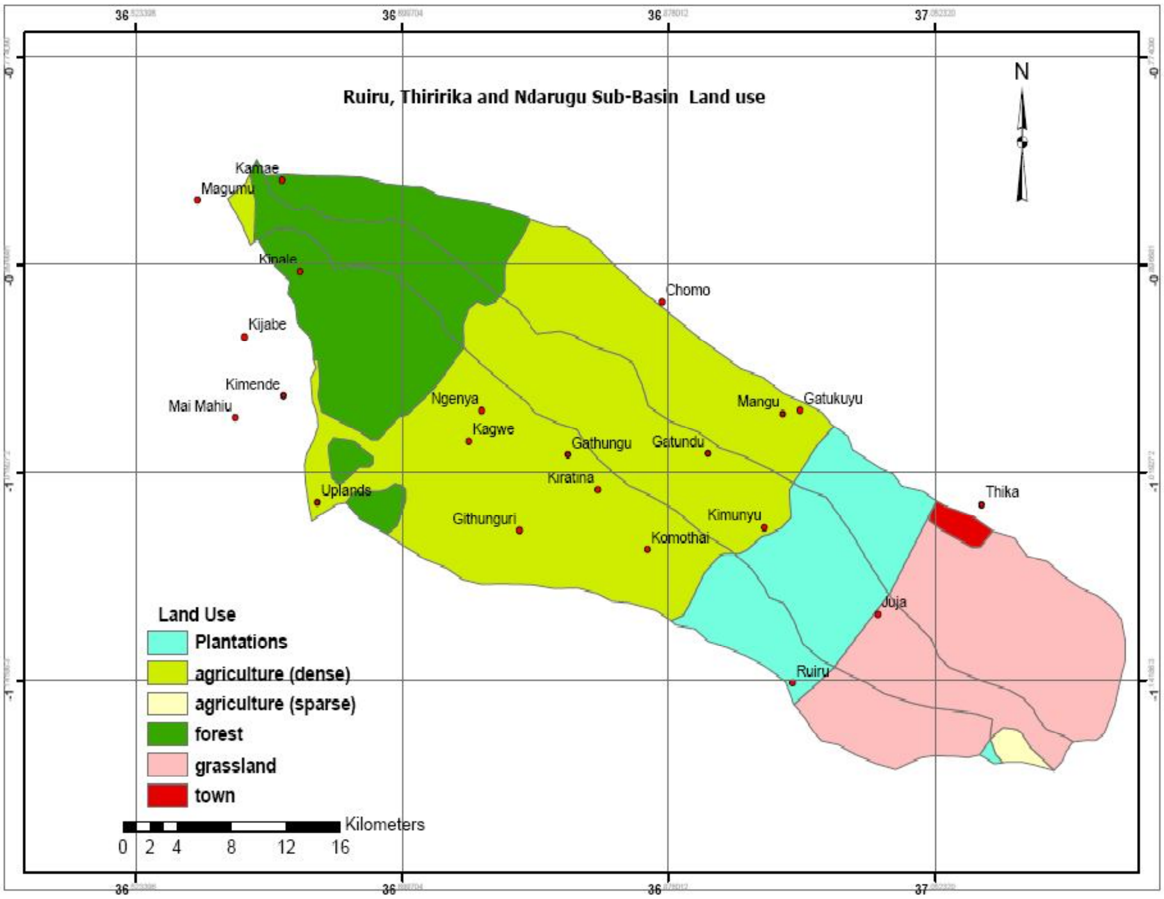

Figure 1.7 Ruiru, Thiririka and Ndarugu Sub-Basin Land use (Source: ILRI, 2008)

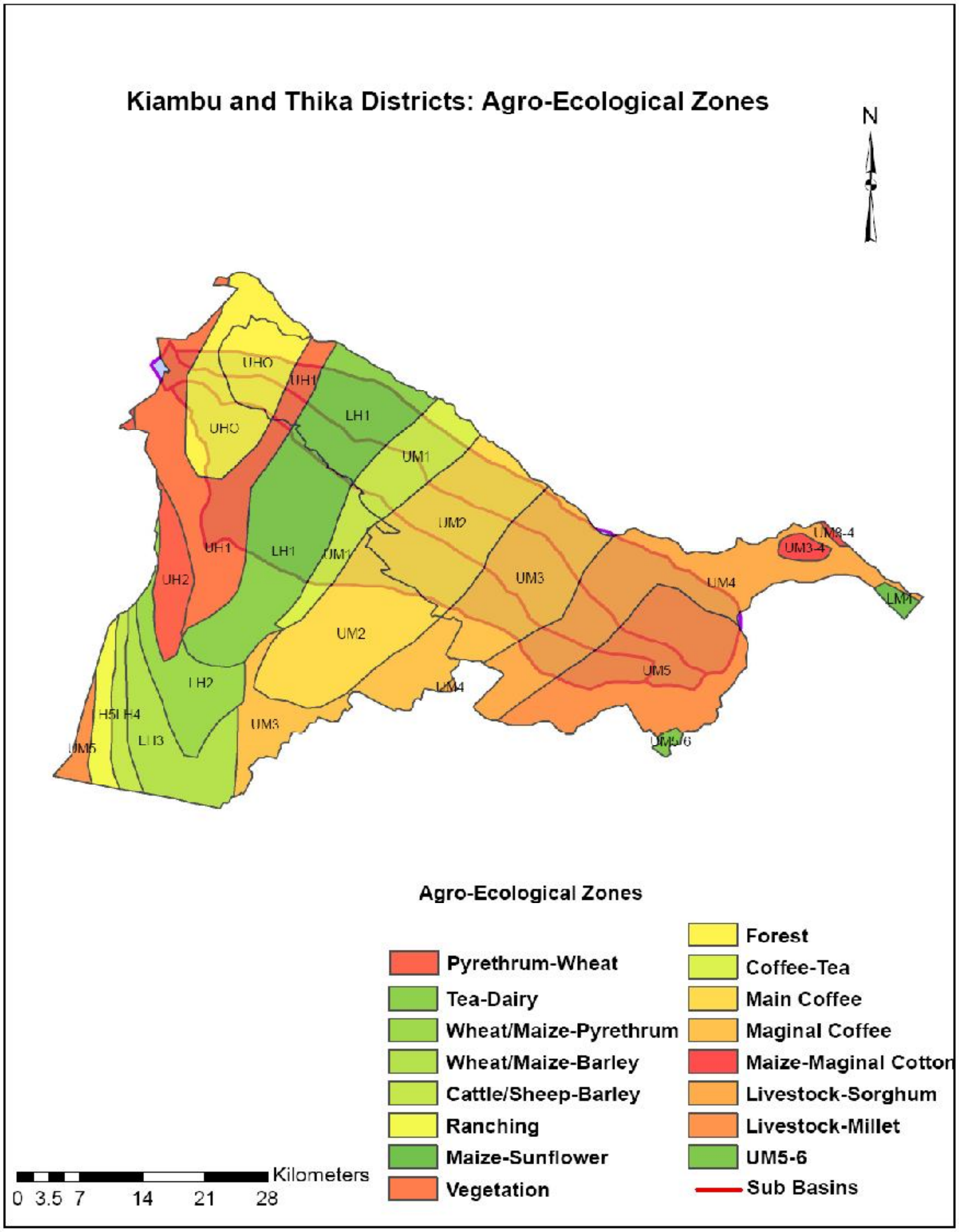

Figure 1.8 Agro-Ecological Zones for Kiambu and Thika districts (Source: MOA, 2006)

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Water Resources Potential and Management in Kenya

According to National Water Master Plan (JICA, 1992), the annual quantity of renewable freshwater resources was 20.2 billion cubic meters (BCM) of surface water. Based on the annual water availability of 20.2 BCM and a current population of 38.6 million people, the per capita endowment of water is 523 m^3 per capita per year (average per capita for the whole of Kenya). The growing population (Figure 2.1) in Ruiru, Thiririka and Ndarugu sub-basins increases the demand for water for domestic use, food security and hydropower to the point where the needs are outstripping supply. This makes orderly economic and social development which depends on reliable water resources more difficult to achieve.

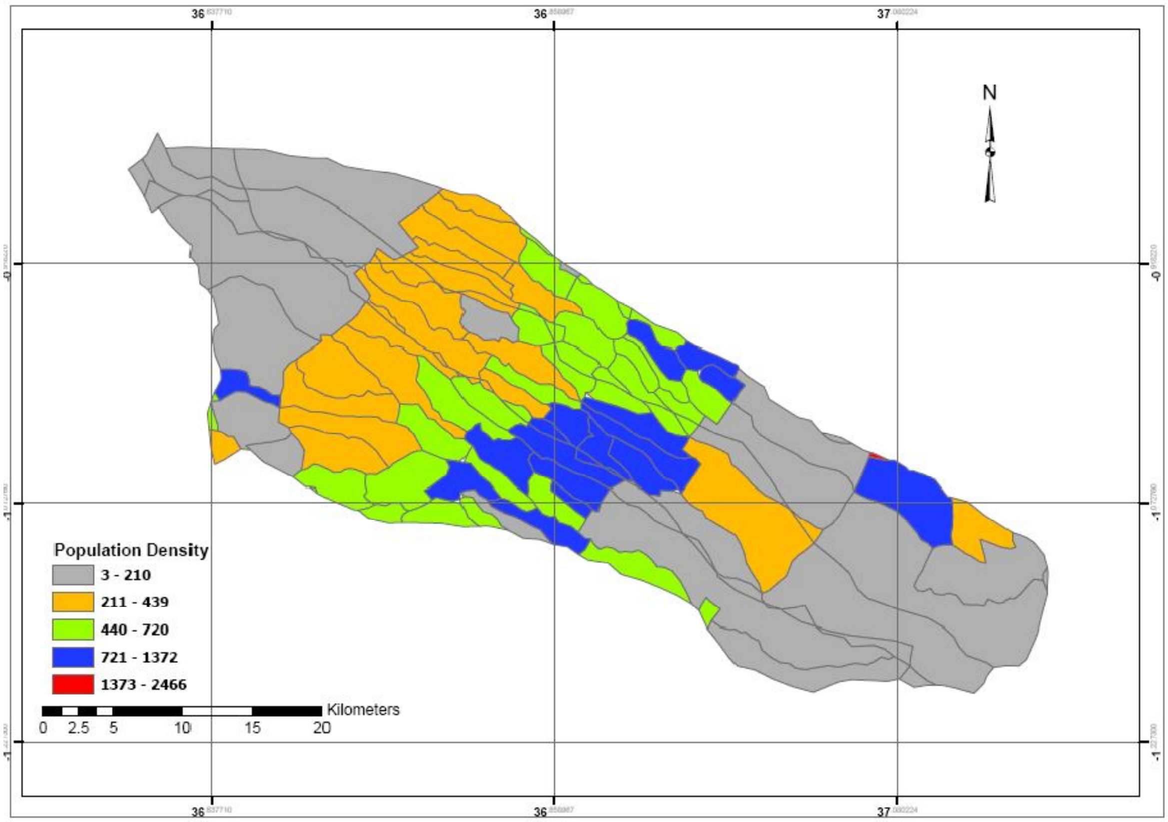

Figure 2.1 Ruiru, Thiririka and Ndarugu Sub-Basin Population Distribution

The National Master Plan indicates that water demands in the important categories of domestic water, industry, agriculture including irrigation, livestock, wildlife and hydropower will increase significantly from 2,073 MCM/year in the year 1990 to 5817 MCM/ year in the year 2010. In order to provide for this increasing demand on the country's water resources, greater care will need to be taken of water resources and more effective planning and project implementation and coordination mechanisms are required. According to the Master Plan, these needs cannot be met without regulation works in rivers through dams and reservoirs.

Sessional Paper Number 1 of 1999 on National Water Policy on Water Resources Management and Development (GOK, 1999) provides the general policy direction that addresses the critical water related issues and challenges. The policy directions include the following; treat water as social and economic good, preservation, conservation and protection of available water resources, supplying adequate amounts of water meeting acceptable standards of various needs, ensuring safe wastewater disposal for environmental protection and developing a sound and sustainable financial system for effective and efficient water resources management, water supply and water borne sewerage collection, treatment and disposal.

The Water Act (GOK, 2002) provides an institutional framework for the management and protection of Kenya's water resources at national, catchment and sub catchment levels. At the sub catchment level water resources users association are established to provide forum for cooperative management of water resources. The Kenyan IWRM plan (WRMA, 2007) intends to contribute to coordinated decision making, ensuring ecological sustainability and meeting the current and future water demands.

Kenya's water resources are distributed over six catchments areas of five drainage basins namely Lake Victoria which comprises a North Catchment and a South Catchment, Rift Valley, Athi, Tana and Ewaso Ng'iro Catchments (Figure 2.2). Athi Catchment covers an area of 58638 km^2 and had a total population of 10.7 million people in 2009 (based on census of 2009) and an average annual population growth rate of 3%. The climate varies from sub- humid in the upper zone, semi-arid in the middle zone and arid in the coastal zone.

Athi is water-scarce catchment with a water availability amounting to 162 m^3 per capita per year (NWMP, 1992). The main economic activity takes place in the large urban centers of the catchment principally in the large urban centers of Nairobi and Mombasa. Agriculturalists live predominantly in the upper part of the catchment and pastoralists in the middle part. Key issues in the Athi catchment relating to water resources situation are acute water scarcity due to higher water demand than water availability, over-exploitation of surface water and ground water resources, pollution of water resources from agro-industries and waste disposal and catchment degradation due to overgrazing and sand harvesting.

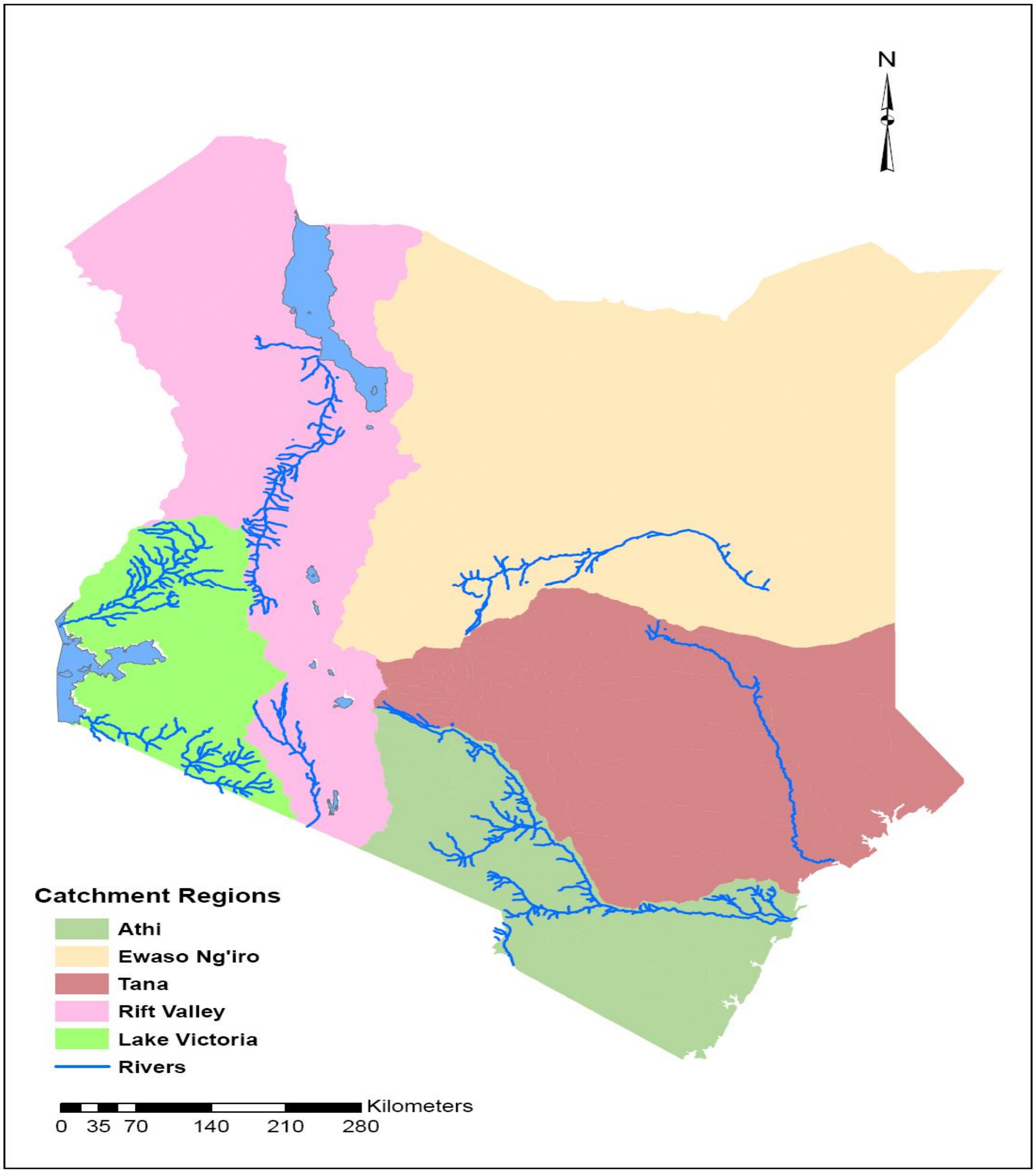

Figure 2.2 Catchments of Kenya (Source: WRMA, 2009)

2.2 Water Use Modeling

Water allocation models estimate the quantity of water available to different users within a river basin at different times. Over the last 30 to 40 years major advances have been made in their development and they are increasingly used to assist in the planning and management of complex water resource systems (Jamieson, 1996). These models help support the analysis of allocation problems involved in complicated hydrological, environmental and socioeconomic constraints and conflicting management objectives (McCartney, 2007). They allow policy makers and managers to gain insight into the potential consequences of policy changes, changes to physical infrastructure and changes in processes that affect runoff such as those due to land use modifications. They can also help set the expectations of different water users with respect to the reliability and security of supply, which can help secure investment in water dependent enterprises (Etchells and Malano, 2005). In some instances models have been integrated within an economic framework, thereby enabling an assessment of the potential economic consequences of different options used for the management of water resources.

Examples of models used in water management are: Water Evaluation and Planning System (WEAP), Hydrologic Engineering Center’s Hydrologic Modeling System (HEC-HMS), AQUARIUS, Volta Basin Water Allocation System (VB-WAS), MIKE BASIN, Resource Allocation Model (REALM) and Water Allocation Scheduling and Monitoring System (WASAM). The HEC-HMS (US ACE, 2000) is designed to simulate the precipitation - runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

VB-WAS(GVP, 2000) is used as decision support tool that allow incorporating the impact of possible future climate conditions and projected water demand scenarios on future water resources management and infrastructure development in the basin. The main purpose of WASAM (Vudhivanich, 1997) is to determine the required discharge of a canal from long term average potential evapotranspiration, crop coefficient and the cropping pattern. It is an irrigation water use model. REALM (Perera *et al.*, 2005) is a generalized computer simulation software package that models the harvesting and bulk distribution of water supply system. It is tool for evaluating changes in the operation of stream flow and water supply systems.whic MIKE BASIN (DHI, 2006) is a multipurpose, GIS-based river basin simulation package. It is designed for analyzing water sharing problems and environmental issues at international, national and project scale. Typical MIKE-BASIN application are solving multi-sector water allocation problems, improving reservoir and hydropower operations, conducting transparent water resources assessment, evaluating irrigation scheme performance and crop yield etc. AQUARIUS (Diaz *et al.*, 2000) is a computer model depicting the temporal and spatial allocation of water flows among competing uses in a river basin. The model focuses on optimization of nonlinear system where supplies and requested demands are prescribed on the system. However, WEAP (SEI, 2005) is distinguished by the integrated approach to simulating water systems and its policy orientation. WEAP evaluates a full range of water development and management options and takes account of multiple and competing uses of water systems. The WEAP model was chosen due its flexibility, scenario approach, ease-of-use and powerful data management and reporting tools.

2.3 WEAP Model

Developed by the Stockholm Environmental Institute (SEI, 2005), the WEAP model was designed to be used to evaluate planning and management issues associated with water resources development. It can be applied to both municipal and agricultural systems and can address a wide range of issues including: sectoral demand analyses, water conservation, water rights and allocation priorities, stream flow simulation, reservoir operation, ecosystem requirements and cost-benefit analysis. The WEAP model has two primary functions:

- Simulation of natural hydrological process (e.g. evaporation, runoff and infiltration) to enable assessment of the availability of water within a catchment; and,
- Simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e. consumptive and non-

consumptive water demands) to enable evaluation of the impact of human water use.

WEAP has been applied in water assessment in dozens of countries, including Kenya (Amani, 2004; Dienya, 2007; Van and Drogers, 2006), South Africa (Herve *et al*., 2003; Mathew and Roberto, 2007a; Mathew and Roberto 2007b) and Turkey (Van *et al*., 2007).

2.3.1 Operational Lay Out of WEAP Model

When the WEAP model is opened, a new area is created. An area is a set of demand sites defined by political or geographical boundary. A GIS-based vector map is then added to the project area. Using the river symbol, the river is drawn from the upstream to the downstream. Stream flow data for the river is added using monthly time series wizard or ReadFromFile method. Urban and agriculture demand sites are then created. Data is entered into the demand sites as annual activity levels e.g. population and acreages and their annual water use rates. The WEAP model is linked to Modflow and Qual2K for groundwater and water quality analysis respectively. A new catchment is created and located near the starting point of the river. The parameters that are inputted in the catchment modeling are area, crop coefficient, effective precipitation, precipitation and evapotranspiration. The detailed model operations are schematically illustrated in Figure 2.3.

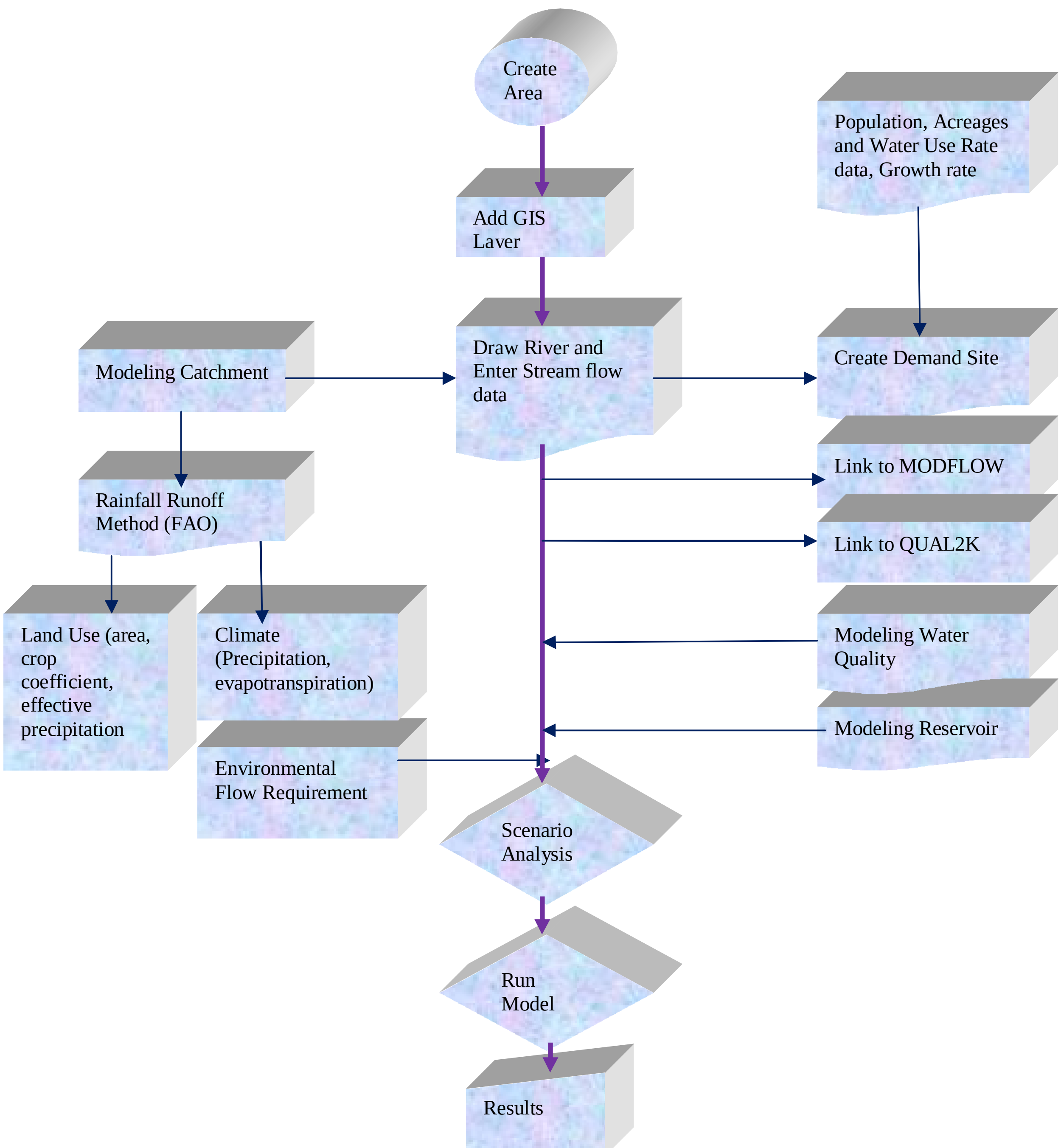

Figure 2.3 Operational layout of WEAP model

2.3.2 WEAP Area

An “area” in WEAP is defined as a self-contained set of data and assumptions. Its geographical extent is typical a river basin. An area is sometimes referred to as a “data set”. A study area can be a set of demand sites defined by political or geographic boundaries. It can also be defined as a specific water supply system such as a river basin or a groundwater aquifer.

2.3.3 Demand Site

A demand site is best defined as a set of water users that share a physical distribution system that are all within a defined region, or share an important withdrawal point.

Demand sites include major cities or towns, individual users, irrigation farms, demands that return to a unique waste water treatment plant and water utilities. Each demand site needs a transmission link from its source and a return link to the river, waste water treatment plant or other allocation. The water demand can computed using equations 1, 2 and 3:

$$Annual\ Demand_{DS} = \sum_{Br}(TotalActivityLevel_{Br} \times WaterUseRate_{Br}) \qquad (1)$$

where Annual Demand represents the amount of water required by each demand and Total Activity Level is the annual level of activity driving demand such as agricultural area, population using water for domestic purposes or industrial output.

$$DemandSiteInflows_{DS} = \sum_{Src} TransLinkOutflow_{Src.DS} \qquad (2)$$

where *TransLinkOutflow* is the flow through each transmission link.

$$Consumption_{DS} = Demand\ Site\ Inflow_{DS} \times Demand\ Site\ Consumption_{DS} \qquad (3)$$

Where

where, DS is the demand site, Br is demand site bottom-level branches and Src is the supply source.

2.3.4 Current Accounts

The Current Accounts represent the basic definition of the water system as it currently exists. The Current Accounts are also assumed to be the starting year of all scenarios. The Current Accounts includes the specification of supply and demand data for the first year of the study on a monthly basis.

2.3.5 Scenario Analysis

Scenarios are self-consistent story – lines of how a future system might evolve over time in a particular socio-economic setting and under a particular set of policy and technology conditions. Scenarios are built and then compared to assess their water requirements, costs, and environmental impacts. Scenarios can address a broad range of "what if" questions, such as: What if population growth and economic development patterns change? What if reservoir operating rules are altered? What if groundwater is more exploited? What if water conservation is introduced? What if ecosystem requirements are tightened? What if a more efficient irrigation technique is implemented? What if climate change alters the hydrology?

2.3.6 Specifying Hydrological Inflows

WEAP has four methods for projecting the water hydrology over the study period: Water Year Method, Expressions, Catchment Runoff and Infiltration and ReadFromFile Method.

2.3.6.1 Water Year Method

The Water Year Method allows one to use historical data in a simplified form and explore the effects of future changes in hydrological patterns. The Water Year Method projects future inflows by varying the inflow data from the Current Accounts.

Water Year Definitions that WEAP uses are Normal, Very Wet, Wet, Dry and Very Dry.

2.3.6.2 Expressions

Inflows can be specified with a mathematical expression. Typical expressions include: constants (e.g., groundwater recharge that doesn't vary over time), a specified value for each month (this is usually how the Current Accounts inflow data is specified when you are using the Water Year Method to project future inflows), or some other relationship (e.g., the head flow for ungauged stream could be modeled as some fraction of the head flow in another river for which good data exists).

2.3.6.3 Catchment Runoff and Infiltration

Catchment Runoff can be directed to rivers and groundwater nodes using a Runoff/Infiltration Link. These flows can be specified directly (for the Rainfall Runoff Method) or WEAP can simulate, using the Soil Moisture Method, the amounts of runoff, soil moisture, and base flow generated by the catchment.

2.3.6.4 ReadFromFile Method

The ReadFromFile function allows one to read annual or monthly data from a text, comma-separated value (CSV) file into any WEAP variable. A text file can contain one or more columns of data for each year or month. The format of the WEAP expression is:

$ReadFromFile(FileName)\ or$

$ReadFromFile(FileName, DataColumnNumber)\ or$

$ReadFromFile(FileName, DataColumnNumber,\ YearOffset)$

2.3.7 Methods for Calculating Demands

There are three methods for calculating demands. These are standard water use method, direct method and FAO crop water requirement approach.

2.3.7.1 Standard Water Use Method

The user determines an appropriate activity level (e.g. persons, households, hectares of land) for each disaggregated level and multiplies these by the appropriate annual water use rate.

2.3.7.2 Direct Method

Demands can be directly read into WEAP from a file or monthly water use rates can be inputted. The data is entered through data view, demand site branch, advanced category and method tab.

2.3.7.3 FAO Crop Requirement Approach

The FAO crop requirement approach is used to represent agricultural demand nodes (SEI, 2005). This approach assumes for each demand site a set of simplified hydrological and agro-hydrological processes such as precipitation, evapotranspiration, and crop growth emphasizing irrigated and rain fed agriculture.

2.3.8 Overview of Catchment Simulation Methods

There is a choice among three methods to simulate catchment processes such as evapotranspiration, runoff, infiltration and irrigation demands. These methods include the Rainfall Runoff Method (FAO), Irrigation Demands Only Method (FAO) and the Soil Moisture Method.

2.3.8.1 Irrigation Demands Only (FAO)

It uses crop coefficients to calculate the potential evapotranspiration in the catchment, then determines any irrigation demand that may be required to fulfill that portion of the evapotranspiration requirement that rainfall cannot meet. It does not simulate runoff or infiltration processes.

2.3.8.2 Rainfall Runoff Method (FAO)

The Rainfall Runoff Method determines evapotranspiration for irrigated and rain fed crops using crop coefficients. The remainder of rainfall not consumed by evaporation is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links.

2.3.8.3 Rainfall Runoff Method (Soil Moisture Model)

The method represents the catchment with two soil layers, as well as the potential for snow accumulation. In the upper layer it simulates evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow, and changes in soil moisture. Base flow routing to the river and soil moisture changes are simulated in the lower layer.

2.3.9 FAO Crop Requirements

FAO crop requirements are calculated assuming a demand site with simplified hydrological and agro-hydrological processes such as precipitation, evapotranspiration and crop growth emphasizing irrigated and rainfall agriculture. The following equations are used to implement this approach where subscript LC is land cover, HU is hydro-unit and I is irrigated.

$$PrecipAvailableForET_{LC} = Precip_{Hu} \times Area_{LC} \times 10^{-5} \times PrecipEffective_{LC} \quad (4)$$

$$ETpotential = ETreference \times Kc_{LC} \times Area_{LC} \times 10^{-5} \quad (5)$$

$$Supply_{LC1} = Supply_{HU} \times (Supply\ Requirement_{LC1} / Supply\ Requirement_{HU}) \quad (6)$$

$$Runoff_{LC} = Max(0, PrecipAvailableForET_{LC} - ETpotential_{LC} + (Precip_{LC} \times (1 - PrecipEffective_{LC})) + (1\text{-}IrrFrac_{LC1} \quad (7)$$

where $Area$ (ha) - Area of land cover

$Precip$ (mm) - Precipitation

$PrecipEffective(\%)$ - Percentage of precipitation that can be used for evapotranspiration

$PrecipAvailableForET(MCM)$ - Precipitation available for evapotranspiration

$K_C(-)$ - FAO crop coefficient

$ETreference(mm)$ - Reference crop evapotranspiration

$ETpotential(MCM)$ - Potential crop evapotranspiration

$IrrFrac(\%)$ - Percentage of supplied water available for ET (i.e. irrigation efficiency)

$SupplyRequirement(MCM)$ - Crop irrigation requirement

$Supply(MCM)$ - Amount supplied to irrigation (calculated by WEAP allocation)

2.3.10 Water Quality Modeling

WEAP tracks water quality, including pollution generation at demand site, waste removal at waste water treatment plants, effluent flows to surface and ground water sources, and water quality modeling in rivers. WEAP uses its built-in BOD model to simulate the changes in the biochemical oxygen demand (BOD) in the river. In order to model BOD, temperature is included as one of the water quality constituents. The initial concentration of a pollutant at the point injection into the stream is calculated from a mass balance using equation 8:

$$c = \frac{Q_w C_w + Q_r C_r}{Q_w + Q_r} \tag{8}$$

where c is the new concentration

Q_w is the flow of waste water discharge (m^3 /time)

C_w is the concentration of the pollutant in the waste water (mg/l)

Q_r is the flow of the receiving water (m^3/time)

C_r is the concentration of the pollutant in the receiving water (mg/l)

The oxygen saturation OS for a segment is estimated as a function of water temperature T,

$$OS = 14.54 - (0.39T) + (0.01T^2) \tag{9}$$

And an analytical solution of the classic Streeter-Phelps model is used to compute oxygen concentrations from point source loads of BOD.

$$O = OS - \left(\frac{k_a}{k_a - k_r}\right)\left(e^{-k_r(L/U)}\right)BOD_{IN} - \left((OS - O_{IN})e^{-k_d(L/U)}\right) \tag{10}$$

Where:

$k_{d=}0.4$; $k_a = 0.95$; and $k_r = 0.4$ are the decomposition, the reaction, and the re-aeration rates, respectively (1/day). L is the reach length (m), U is the velocity of the water in the reach. O_{IN} is the oxygen concentration (mg/l) at the top of the reach and BOD_{IN} is the concentration of the pollutant loading (mg/l) at the top of the reach.

BOD removal is calculated using equation 11, 12 and 13:

$$BOD = BOD_{IN}\left(e^{-k_{rBOD}(L/U)}\right) \tag{11}$$

The removal rate k_{rBOD} is influenced by several factors, including temperature, settling velocity of the particles, and water depth. Chapra (1997) provides an expression for k_{rBOD} as,

$$k_{rBOD} = k_{d2o}^{(1.047(T-20)} + \frac{V_S}{H} \tag{12}$$

where T is the water temperature (in degrees Celsius), H is the depth of the water, and V_s is the settling velocity. In addition, k_{d20} is defined (at a reference temperature of 20 degrees Celsius) as,

$$k_{d20} = 0.3\left(\frac{H}{8}\right)^{-0.434} \tag{13}$$

2.3.11 Proposed Reservoirs

A reservoir is the artificial body of water that forms adjacent to a storage dam. Many of the modern reservoirs that operate today in unison with dams serve two or more purposes. The most common purposes of these reservoirs are generating hydroelectric power, provide flood control, store water, enable irrigation and provide recreational opportunities. In Ruiru and Ndarugu River Basin, two dams were proposed i.e. Ruiru A dam and Ndarugu dam. Ruiru A dam is located on the Ruiru River about 2 km downstream of the existing Ruiru dam which is one of the present sources of water for Nairobi through pipeline supply. Ndarugu dam is located on the Ndarugu River just downstream of the confluence of the two rivers; Komu and Ndarugu (Figure 2.4). The dam was proposed for supplying water to Nairobi and its environs ((JICA, 1992). The reservoir volume for Ruiru A dam and Ndarugu dam is 19 MCM each.

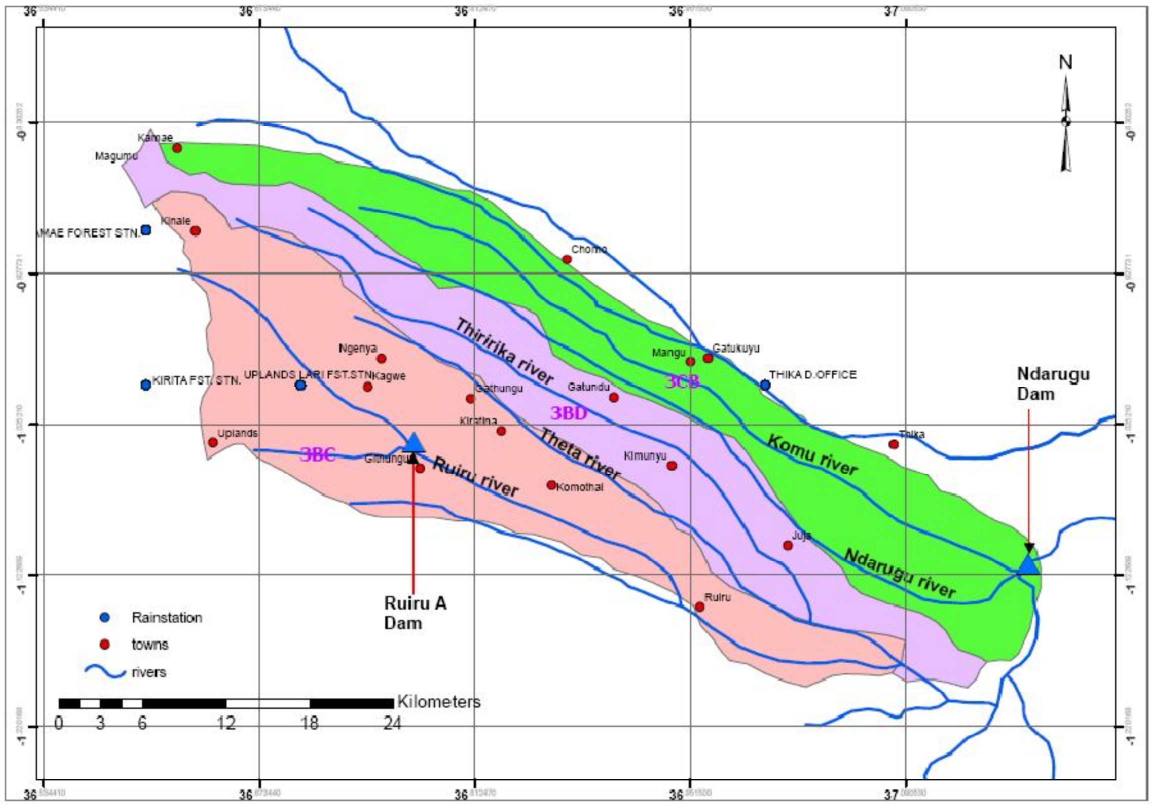

Figure 2.4 Locations of proposed dams in Ruiru and Ndarugu Rivers

Reservoir storage is divided into four zones or pools. These include, the flood control zone, conservation zone, buffer zone and inactive zone (Figure 2.5). The conservation and buffer pools constitute the reservoirs active storage. WEAP will ensure that the flood control zone is always kept vacant i.e. the volume of the water in the reservoir cannot exceed the top of the conservation pool.

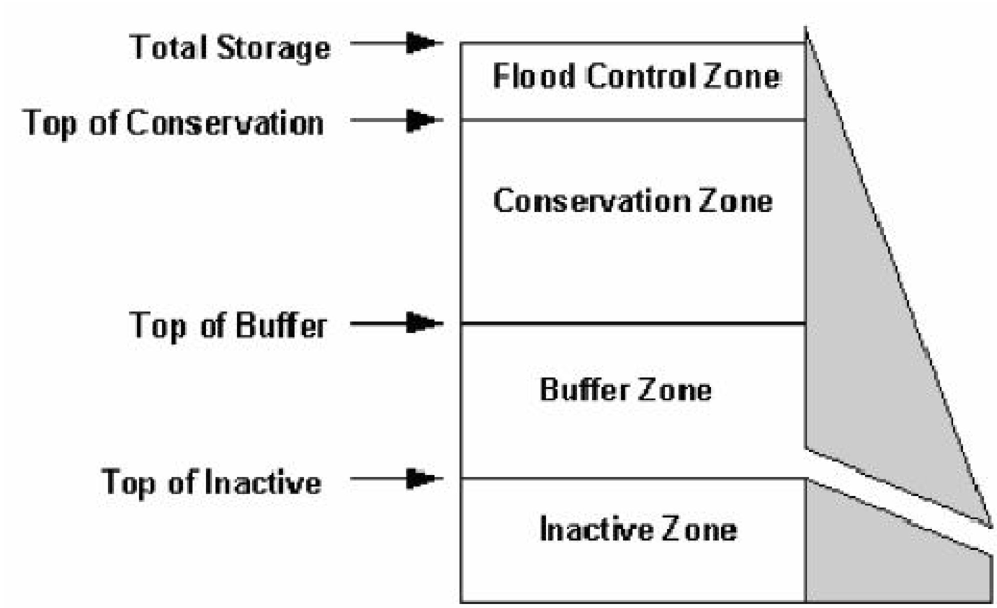

Figure 2.5 The different reservoir storage volumes

A reservoir's (Res) storage in the first month (m) of the simulation is specified as data.

$$BeginMonthStorage_{Res,m} = Initialstorage_{Res,m} \quad \text{for } m = 1 \tag{14}$$

Thereafter, it begins each month with the storage from the end of the previous month.

$$BeginMonthStorage_{Res,m} = EndMonthStorage_{Res,m-1} \quad \text{for } \; m > 1 \tag{15}$$

This beginning storage level is adjusted for evaporation as:

$$BeginMonthElevation_{Res} = VolumeToElevation(BeginMonthStorage_{Res}) \quad (16)$$

The elevation is reduced by the evaporation rate as:

$$AdjustedBeginMonthElevation_{Res} = BeginMonthElevation_{Res} - EvaporationRate_{Res} \quad (17)$$

Then the adjusted volume is converted into a volume as:

$$AdjustedBeginMonthStorage_{Res} = ElevationToVolume(AdjustedBeginMonthElevation_{Res}) \quad (18)$$

A reservoir operating rules determines how much water is available in a given month for release, to satisfy demand and in stream flow requirement, and for flood control. These rules operate on the available resource for the month. This storage level for operation is the adjusted amount at the beginning of the month, plus inflow from upstream and return flows from demand sites(DS) and treatment plants(TP).

$$StorageForOperation_{Res} = AdjustedBeginMonthStorage_{Res} + Upstream_{Res} + \sum_{DS} DSReturnFlow_{DS,Res} + \sum_{TP} TPReturnFlow_{TP,Res} \quad (19)$$

WEAP will release only as much of the storage available for release as is needed to satisfy demand and in stream flow requirements, in the context of releases from other reservoirs and withdrawals from rivers and other sources.

$$Outflow_{Res} = DownstreamOutflow_{Res} + \sum_{DS} TransLinkInflow_{Res,DS} \quad (20)$$

where

$$Outflow_{Res} \leq StorageAvailableForRelease_{Res} \quad (21)$$

The storage at the end of the month is the storage for operation minus the outflow.

$$EndMonthStorage_{Res} = StorageForOperation_{Res} - Outflow_{Res} \quad (22)$$

The change in storage is the difference between the storage at the beginning and the end of the month.

$$IncreaseInStorage_{Res} = EndMonthStorage_{Res} - BeginMonthStorage_{Res} \quad (23)$$

2.3.12 Environmental Flow

Environmental flow is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. Environmental flows provide critical contributions to river health, economic development and poverty alleviation. They ensure the continued availability of the many benefits that healthy river and groundwater systems bring to the society. Environmental flows are considered as an integral part of the modern management of a river basin. The requirement of water quantity and quality for environmental flows in estuaries are to ensure that physical, chemical and biological balances in the ecosystem are well maintained. The price of not providing environmental flow should not be underestimated. It is increasingly clear that, failure to meet environmental flow requirements has disastrous consequences for many rivers. The absence of environmental flow puts at risk the very existence of ecosystems, people and economies. The total environmental flow is:

$$W_{river} = W_e + W_{S+}W_b + Max(W_{t,}W_w) \quad (24)$$

where:

$$W_e = EA_{water} + \alpha EA_{plant} - PA_{total} \tag{25}$$

W_e is net requirement for evaporation, E and P are the average potential evaporation and precipitation in the area respectively

A_{total} is the total wetland area

A_{water} is the water surface area

A_{plant} is the area of the vegetation cover

α is the reduced evaporation from vegetation covered area compared to the potential evaporation.

$$W_s = \beta HA_s \tag{26}$$

W_s is water requirement of soil

β is the field water capacity, H is the soil thickness and A_s is the soil area

$$W_b = \sum_{i=1}^{n} W_{bi} = \sum_{i=1}^{n} Y_i W_i A_B \tag{27}$$

where W_{bi} is a water requirement for i^{th} species, n is the number of species, Y is the water content of biota, A_B is the area of biological distribution.

$$W_w = u\gamma A_w H \tag{28}$$

W_w is water requirement for wildlife habitat, u is the ratio of water surface to total wetland area, γ is the water exchange period(time^{-1}), A_w is the total area of wetland, H is the average water depth within the water surface area.

$$W_t = \frac{Q_i}{C_i} \tag{29}$$

where W_t is water requirement for sediment transport, Q_i is the quantity of alluvial sediment in the estuary; C_i is the sediment carrying capacity (kg/m^3)

2.3.12.1 Environmental Flow Assessment

In the most recent review of international environmental flows assessments, Tharme (2003) recorded 207 different methods within 44 countries. Several different categorizations of these methods exist, three of which are shown in Table 2.1.

Table 2.1 Environmental Flow Assessment Methods

Organization	**Categorization of EFA**	**Sub-category**	**Example**
IUCN (Dyson et al., 2003)	Methods	Look-up tables	Hydrological (e.g. Q95 Index) Ecological (e.g. Tennant Method)
		Desk-top analyses	Hydrological (e.g. Richter Method) Hydraulic (e.g. Wetted Perimeter Method) Ecological
		Functional analyses	Building Block Method, Expert Panel Assessment Method, Benchmarking Methodology
		Habitat modeling	PHABSIM
	Approaches		Expert Team Approach, Stakeholder

			Approach (expert and non-expert)
	Frameworks		Instream Flow Incremental Method, Downstream Response to Imposed Flow Transformation
World Bank (Brown & King, 2003)	Prescriptive approaches	Hydrological Index Methods	Tennant Method
		Hydraulic Rating Methods	Wetted Perimeter Method
		Expert Panels	
		Holistic Approaches	Building Block Method
	Interactive approaches		Instream Flow Incremental Method, Downstream Response to Imposed Flow Transformation
IWMI (Tharme, 2003)	**Hydrological index methods**		**Tennant Method**
	Hydraulic rating methods		Wetted Perimeter Method
	Habitat simulation methodologies		Instream Flow Incremental Method
	Holistic methodologies		Building Block Method, Downstream Response to Imposed Flow Transformation, Expert Panel Benchmarking Methodology

(Source: Louise and Katherine, 2006)

2.3.12.2 Indicators of Hydrologic Alteration (IHA) Model

The Indicators of Hydrologic Alteration (IHA) software was developed by The Nature Conservancy (TNC, 2009) as an easy to use tool for calculating the characteristics of natural and altered hydrologic regimes. The IHA software uses daily river flow data for its calculations. The IHA will calculate a total of 67 statistical parameters. These parameters are subdivided into two groups, the IHA parameters and the Environmental Flow Components (EFC) parameters. The IHA calculates parameters of five different types of Environmental Flow Components (EFC); low flows, extreme low flows, high pulses, small floods and large floods. Table 2.2 gives a summary of Environmental Flow Components (EFC) parameters and their ecosystem influences.

Table 2.2 Environmental Flow Components

EFC Type	Hydrologic Parameters	Ecosystem Influences
1. Monthly low flows	Mean or median values of low flows during each calendar month	Provide adequate habitat for aquatic organisms • Maintain suitable water temperatures, dissolved oxygen, and water chemistry • Maintain water table levels in floodplain, soil moisture for plants • Provide drinking water for terrestrial animals • Keep fish and amphibian eggs suspended • Enable fish to move to feeding and spawning areas • Support hyporheic organisms (living in saturated sediments)
2. Extreme low flows	Frequency of extreme low flows during each water year or season Mean or median values of extreme low flow event: • Duration (days) • Peak flow (minimum flow during event) • Timing (Julian date of peak flow)	Enable recruitment of certain floodplain plant species • Purge invasive, introduced species from aquatic and riparian communities • Concentrate prey into limited areas to benefit predators
3. High flow pulses	Frequency of high flow pulses during each water year or season Mean or median values of high flow pulse event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow)	Shape physical character of river channel, including pools, riffles • Determine size of streambed substrates (sand, gravel, cobble) • Prevent riparian vegetation from encroaching into channel • Restore normal water quality conditions after prolonged low flows, flushing away waste products and pollutants • Aerate eggs in spawning gravels, prevent siltation • Maintain suitable salinity conditions in estuaries

	• Rise and fall rates	
4. Small floods	Frequency of small floods during each water year or season Mean or median values of small flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates	Applies to small and large floods: • Provide migration and spawning cues for fish • Trigger new phase in life cycle (i.e. insects) • Enable fish to spawn in floodplain, provide nursery area for juvenile fish • Provide new feeding opportunities for fish, waterfowl • Recharge floodplain water table • Maintain diversity in floodplain forest types through prolonged inundation (i.e. different plant species have different tolerances) • Control distribution and abundance of plants on floodplain • Deposit nutrients on floodplain
5. Large floods	Frequency of large floods during each water year or season Mean or median values of large flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates	Applies to small and large floods: • Maintain balance of species in aquatic and riparian communities • Create sites for recruitment of colonizing plants • Shape physical habitats of floodplain • Deposit gravel and cobbles in spawning areas • Flush organism materials (food) and woody debris (habitat structures) into channel • Purge invasive, introduced species from aquatic and riparian communities • Disburse seeds and fruits of riparian plants • Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes) • Provide plant seedlings with prolonged access to soil moisture

CHAPTER THREE

METHODOLOGY

The WEAP model uses population and agricultural areas as activity levels in the demand sites. Annual activity level is inputted in the model to give annual water demand. Stream flow data is inputted in the WEAP model to cater for the supply. The supply is then connected to the demand site. Catchment area, crop coefficients, effective precipitation, evapotranspiration and precipitation are inputted in the WEAP model to simulate run off from the catchment using the Rainfall Runoff Method as shown in Figure 3.1. The simulated flow is used in WEAP model for comparison with the measured stream flow in the process of calibration.

3.1 Documentation of major water demands and point pollution in the river basin

The types of data collected in this research were primary and secondary data. The primary data collected were locations of demand sites, intake points, point pollution points and water samples along the three rivers. The secondary data collected are populations, stream flow, acreages of area under irrigation, temperature, humidity, wind speed, sunshine hours, radiation and evapotranspiration. Stream flow data was collected from the Ministry of Water and Irrigation and Water Resources Management Authority in Nairobi. Climatic data was collected from the Meteorological Department in Nairobi. Three field surveys and observation were carried out along the river basin and the coordinates and elevations collected using the Global Positioning System (GPS). Water samples were collected for both the upstream and downstream of the three rivers during the dry and wet season. The water samples collected were analyzed in the University laboratory and their results analyzed.

3.1.1 Data Collection

Most of the data used in the study were collected from Ministry of Water and Irrigation, Water Resources Management Authority Regional offices in Machakos and Kiambu, Central Bureau of Statistics, Meteorological Department in Nairobi and Agricultural Offices in Thika and Ruiru. This data include population, discharge, agriculture, rainfall and other climatic data.

3.1.1.1 Demand Sites

Field visits were carried out in the basin in the month of January 2009. The Global Positioning System (GPS) was used to determine the coordinates of the water use sites and abstraction points; and altitudes of towns, institutions, farms and point pollutions.

3.1.1.2 Population Data

The population data for the 2009 census for Ruiru, Thiririka and Ndarugu Sub-Basins was obtained from District Statistics Office in Thika and Kiambu, and Central Berea of Statistics in Nairobi. The population data was inputted as Annual Activity Levels and multiplied by the Annual Water Use Rate to obtain the total annual water demand. The population data was segregated for institutions, municipalities and townships. The

Annual Water Use Rate for various demand sites were based on the Ministry of Water and Irrigation Design Manual (MWI, 2006) as shown in Table 3.1.

Table 3.1 Summary of Water Use Rates (Source: MWI, 2006)

Demand Level	Daily Water Use Rate(l/day)
Rural(high potential)	60
Urban(medium class housing)	150
Urban(high class housing)	250

An Activity Level is the level of any activity that drives demand e.g. population. The population data and population distribution for various divisions in the basin as obtained from 2009 population census are shown in Table 3.2 and Figure 3.2.

Table 3.2 Population data for divisions in the sub-basins (Source: CBS, 2009)

Division	Male	Female	Total
Ruiru	56982	52592	241007
Juja	21613	19523	79772
Gatundu	54277	59422	214791
Nairobi	1153828	989426	3138369

Growth rate was localized for every division. 'GrowthFrom' function of the model was used to calculate future population of various demand sites. The GrowthFrom function calculates a value in any given year using a growth rate from the StartYear. The StartYear can be any year, past, present, or future. In this study, 1980 was used as a StartYear. The function syntaxes as:

$$GrowthFrom(GrowthRate, StartYear, StartValue)$$

3.1.1.3 Discharge Data

The discharge data were obtained from the Ministry of Water and Irrigation (Nairobi) and Water Resources Management Regional Office in Machakos and Sub-Regional Office in Kiambu. Three rivers were used for the study. The rivers are Ndarugu, Thirirka and Ruiru rivers. In Ndarugu River, three river gauging stations were used for the study. The gauging stations for Ndarugu River are 3CB05, 3CB02 and 3CB07. The gauging stations for Thiririka River are 3BD05, 3BD08 and 3BD04. The gauging stations for Ruiru River are 3BC12, 3BC08 and 3BC13.The daily discharges for 3CB05, 3BD05 and 3BC12 (Figure A.4.1, Figure A.4.2 and Figure A.4.3) was summed up to give the mean monthly flows. The gauging stations that were used in the study have been summarized in Table 3.3 and their locations are shown in Figure 3.1. Missing data were calculated using the linear regression formula (Ronald and Raymond, 1989) using equations 30, 31 and 32:

$$Y = a + bX \tag{30}$$

where

$$a = \frac{\sum_{i=1}^{n} Y_i - b\sum_{i=1}^{n} X_i}{n} \tag{31}$$

and

$$b = \frac{n\sum_{i=1}^{n} X_i Y_i - (\sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{n\sum_{i=1}^{n} X_i^2 - (\sum_{i=1}^{n} X_i)^2} \tag{32}$$

where Y = Daily stream flow at a downstream gauging station in cumecs

X = Daily stream flow at an upstream gauging station in cumecs

n = Number of observation of the daily stream flow

$\sum_{i=1}^{n} Y_i$ = Sum of daily stream flow at the downstream gauging station

$\sum_{i=1}^{n} X_i$ = Sum of daily stream flow at the upstream gauging station

$\sum_{i=1}^{n} X_i Y_i$ = The product of the daily stream flows for upstream and downstream gauging stations

$\sum_{i=1}^{n} X_i^2$ = Sum of the square of upstream daily stream flow

Table 3.3 Stream flow data for nine gauging stations

Gauging Station	River	Period	Percentage of missing data
3CB05	Ndarugu	1956 - 1994	14.
3CB02	Ndarugu	1960 - 2000	14
3CB07	Ruabora	1964 - 1990	7
3BD05	Thiririka	1974 - 1987	30
3BD08	Thiririka	1960 - 1995	8
3BD04	Thiririka	1946 - 1989	13
3BC12	Ruiru	1946 - 2000	6
3BC08	Ruiru	1977 - 1995	12
3BC13	Kamathai	1958 - 1995	11

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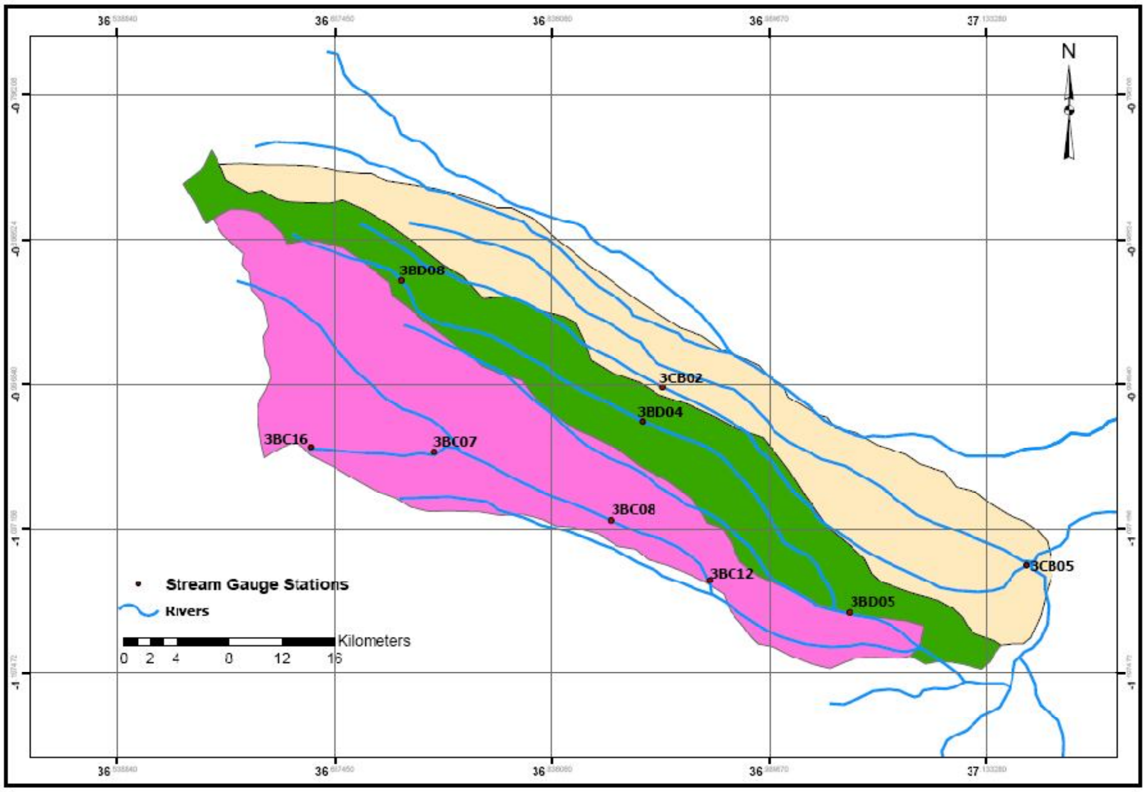


Figure 3.1 Ruiru, Thiririka and Ndarugu River Basin Stream Gauge Stations

The other gauging stations data were used to generate missing data using linear regression.

Stream flow data for the year 1980 was inputted using Monthly Time Series Wizard. The ReadFromFile function was used to read monthly stream flow data from a comma-separated value (CSV) text file into the WEAP model. The monthly data were from 1981 to 1993 for Ndarugu River, 1981 to 1987 for Thiririka River and 1981 to 1999 for Ruiru River.

3.1.1.4 Agriculture Data

The area under irrigation along Ruiru, Thiririka and Ndarugu sub-basins was obtained from the Irrigation Department in Thika and Kiambu. Acreages for different types of crops along the basin were obtained from Agriculture Department in Thika and Kiambu.

The annual water use rate for sprinkler irrigation system was calculated using equation 33 (FAO, 2001):

$$Volume\ of\ water\ applied\ per\ ha\ per\ year(m^3) = 10 * A * d/E * 365/F \tag{33}$$

where:

A = area proposed for irrigation (ha)

d = depth of water application (mm)

E = irrigation efficiency

IF = irrigation frequency

$$d = (FC - PWP) * RZD * P \tag{34}$$

where:

FC = soil moisture at field capacity (mm/m)

PWP = soil moisture at the permanent wilting point (mm/m)

RZD = the depth of soil that the roots exploit effectively (m)

P = the allowable portion of available moisture permitted for depletion by the crop before the next irrigation.

$$IF = d / W_u \tag{35}$$

where:

IF = Irrigation Frequency

d = depth of water application

Wu = peak daily water use rate

3.1.1.5 Water Quality Data

Water samples were collected from the upstream of the three rivers in Gatundu and Githunguri area and downstream of the three rivers at Kalimoni primary school and Juja farm. The water samples were collected during the dry season in August, 2009 and during the rainy season in January, 2010. The water quality parameters that were analyzed are Biochemical Oxygen Demand (BOD), Total Suspended Solids, Total Dissolved Solids, Electrical Conductivity, Chloride, Turbidity and Copper. Temperature was also modeled in WEAP. The water quality parameters were entered into the WEAP model at various demand sites. The City Council of Nairobi effluent discharge standards into the environment were used to compare with the measured water quality parameters (Table A.6.7). Temperatures were entered into the WEAP model using monthly time wizard series from the year 1980 to 2008.

3.1.1.6 Rainfall Data

The WEAP model is based on the premise that at the most basic level, water supply is defined by the amount of precipitation that falls on a watershed. Rainfall data is of utmost importance for the simulation of the catchment process. The rainfall data was obtained from the Kenya Meteorological Department and Ministry of Water and Irrigation, Nairobi. Data for eight stations were used in the analysis. The stations are Ruiru Power Station, Iganjo Farm, Ruiru, Tatu Estate, Ruiru Jacaranda Coffee, Ruiru Juja Sisal Farm, Thika Met Station, Mangu High School and Juja House as shown in Table 3.4 and Figure 3.2. The average precipitation for Ruiru Power Station, Iganjo Farm, Ruiru, Tatu Estate and Ruiru Jacaranda Coffee were used for simulation in Ruiru River (Figure A.5.2). The average precipitation for Ruiru Juja Sisal Farm, Thika Met Station, Mangu High School and Juja House were used for simulation for Ndarugu and Thiririka Rivers (Figure A.5.1). Rainfall data for the year 1980 were inputted using Monthly Time Series Wizard. The rainfall data for the year 1981 to 2000 were inputted using ReadFromFile function. Using rainfall runoff method, evaporation for irrigated and rain fed crops in the catchment shall be computed. The runoff from the catchment is added to the total flow in the river. The average precipitation P_{av} was calculated using equation 36:

$$P_{av} = \sum_{i=1}^{n} Pi \div N \tag{36}$$

where Pi = the precipitation at station i, and N= the total number of rain gauge stations

The effective precipitation was computed by FAO CROPWAT 8.0 model using the USDA soil conservation method (equations 37-38):

$$P_{eff} = (P \times (125 - 0.2 \times 3P))/125 \qquad \text{for P} \leq 250/3\text{mm} \qquad (37)$$

$$P_{eff} = 125/3 + 0.1P \qquad \text{for P} > 250/3\text{mm} \qquad (38)$$

Table 3.4 Rainfall stations used in the study

Station No	Station Name	Element Name	Year
9136005	Ruiru Power Station	Precipitation; Monthly Total	1980 - 1991
9136031	Iganjo Farm, Ruiru	Precipitation; Monthly Total	1980 - 2007
9136053	Tatu Estate	Precipitation; Monthly Total	1980 - 1996
9136084	Ruiru Jacaranda Coffee	Precipitation; Monthly Total	1980 - 2007
9137019	Ruiru Juja Sisal Farm	Precipitation; Monthly Total	1980 - 1988
9137048	Thika Met Station	Precipitation; Monthly Total	1980 - 2007
9137123	Mangu High School	Precipitation: Monthly Total	1980 - 2005
9137214	Juja House	Precipitation; Monthly Total	1999 - 2007

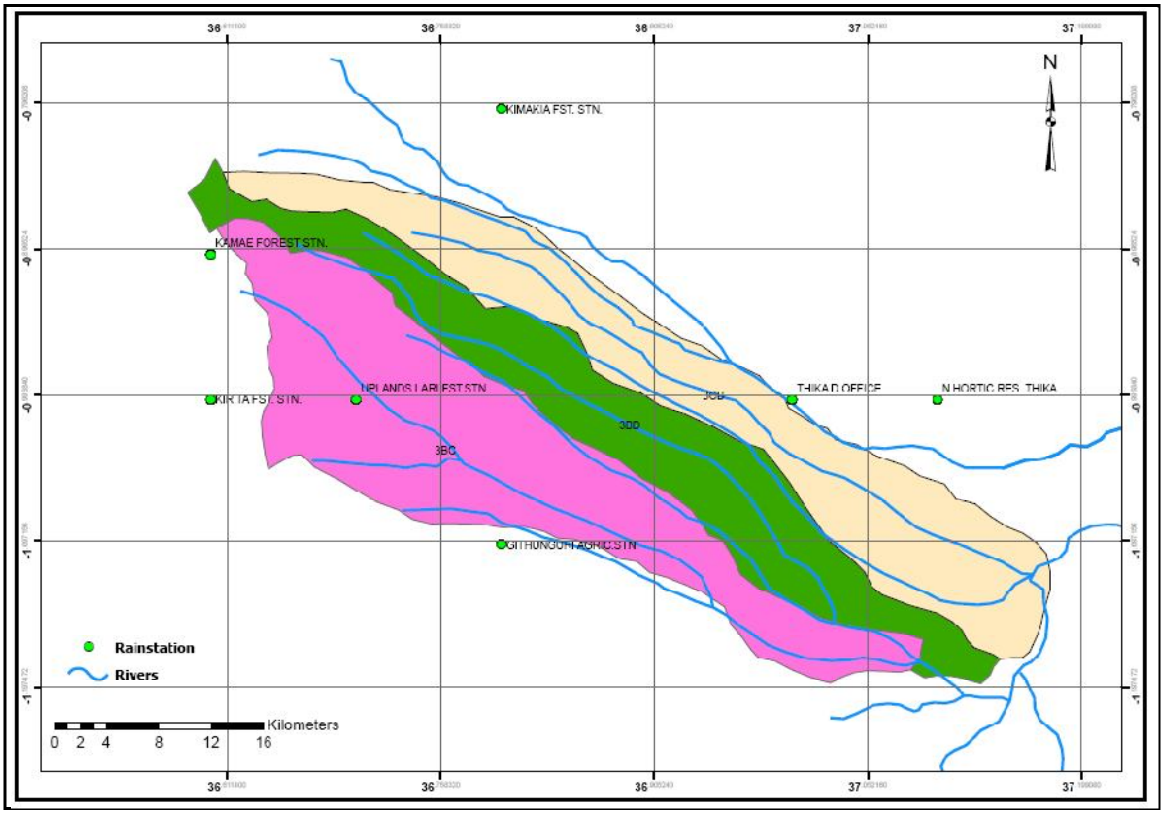


Figure 3.2 Ruiru, Thiririka and Ndarugu River Basin Rain Gauge Stations

3.1.1.7 Other Climatic Data

Other climatic data that were collected are minimum temperature, maximum temperature, percentage humidity, sunshine hours and wind speed (Table 3.5). This data was collected from Meteorological Department, Nairobi. This data was used to compute Evapotraspiration (ET_o) using FAO CROPWAT 8.0 model which is based on Penman-Monteith model (FAO, 1998) (equation 39):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{39}$$

where:

ET_o is reference evapotranspiration [mm day^{-1}],

R_n is net radiation at the crop surface [MJ m^{-2} day^{-1}],

G is soil heat flux density [MJ m^{-2} day^{-1}],

T is mean daily air temperature at 2 m height [°C],

u_2 is wind speed at 2 m height [m s^{-1}],

e_s is saturation vapour pressure [kPa],

e_a is actual vapour pressure [kPa],

$e_s - e_a$ is saturation vapour pressure deficit [kPa],

Δ slope vapour pressure curve [kPa °C^{-1}],

γ psychrometric constant [kPa °C^{-1}].

Table 3.5 Climatic data for Thika Agro-Meteorological station

Altitude 1477m			Latitude 1.00 ^{0}S			Longitude 37.00 ^{0}E	
Month	Minimum Temperature	Maximum Temperature	Humidity	Wind	Sunshine	Radiation	ET_0
	℃	℃	%	Km/day	hours	MJ/m^2/day	Mm/day
January	13.2	26.3	61	288.9	9.3	23.3	4.89
February	13.3	27.7	54.9	288.9	9.3	23.9	5.36
March	14.3	27.8	60.5	288.9	8.4	22.7	5.12
April	15.5	25.6	69.5	244.5	6.7	19.4	4.16
May	15.0	24.8	70.1	222.2	5.9	17.1	3.68
June	13.0	23.8	69.6	222.2	5.0	15.2	3.32
July	12.2	22.7	69.8	222.2	3.8	13.7	3.04
August	12.1	23.5	68.9	222.2	3.9	14.6	3.21
September	12.9	26.0	60.6	266.6	5.7	18.1	4.27
October	14.1	26.5	61.2	266.6	7.3	20.7	4.67
November	14.6	24.8	70.7	266.6	7.4	20.4	4.18
December	13.7	24.8	67	288.9	8.5	21.7	4.40
Average	13.7	25.4	65	257	6.8	19.2	4.19

3.2 Calibration and Validation of the WEAP Model

3.2.1 GIS data processing

Topographical sheets for Ruiru, Thiririka and Ndarugu Sub-Basins (131/1, 134/2, 134/3, 134/4, 135/1, 135/3, 148/1, 148/2, 149/1) were used to digitize the rivers in ARC GIS and a shape file was created for the three rivers. The GIS layer (shape file) was imported into the WEAP model.

3.2.2 Base flow separation

Base flow separation is performed to determine the portion of the hydrograph attributed to base flow. Base flow separation techniques use the time-series record of stream flow to derive the base flow signature. The common separation methods are either graphical which tend to focus on defining the points where base flow intersects the rising and falling limbs of the quick flow response, or involve filtering where data processing of the entire stream hydrograph derives a base flow hydrograph. Filtering methods process the entire stream hydrograph to derive a base flow hydrograph. Recursive digital filters, which are routine tools in signal analysis, are commonly used to remove the high-frequency quick flow signal to derive a low-frequency base flow signal. In this study, base flow separation was done using BaseJumper separation model (SKM, 2007). The digital filter is based on the theory described by Nathan and McMahon (1990) and uses the Lyne and Hollick filter (equation 40):

$$q_f(i) = \alpha q_f(i-1) + [q(i) - q(i-1) * (1-\alpha)/2] \quad (40)$$

where:

For $q_f(i) \geq 0$

where:

$q_f(i)$ is the filtered quick flow response for the i^{th} sampling instant.

$q(i)$ is the original stream flow for i^{th}sampling instant.

α is the filter parameter that enables the shape of the separation to be altered.

After applying the equation, the base flow $(q_b(i))$ is equal to $q(i) - q_f(i)$. If $q(i)$ is less than zero, then $q_b(i)$ is set to $q(i)$.

The filter runs in three passes – the first and third passes are "forward" passes using the equation above, whereas the second pass is "backward" pass using *i+1* rather than *i-1* in the equation. In the first pass, $q(i)$ is computed stream flow; in the second pass it is the computed base flow from the first pass, and in the third pass, it is the computed base flow from the second pass. These passes act to smooth the data.

The daily runoff that was generated by the BaseJumper model were summed up for the entire month to give monthly run off. The monthly run off was then inputted into WEAP model for comparison with the simulated monthly flows.

3.2.3 Data input into the WEAP model

3.2.3.1 Data preparation

Stream flow, rainfall and effective rainfall data were prepared in a comma separated value format and saved as text file. The data was then read by using the ReadFromFile method of the WEAP model.

3.2.3.2 Schematic set up

In the schematic part of WEAP the watershed was delineated, and rivers, demands sites were specified. GIS maps of rivers and river basins were used to determine the exact location of the streams in WEAP. The study focused on irrigation schemes, domestic supply, municipal (towns) and institutions. Juja town, Jomo Kenyatta University and Ruiru town were included in the WEAP as shown in Figure 3.3. In the catchment area, the rainfall runoff method was used to generate inflow into the river by calculating the difference between precipitation and evaporation.

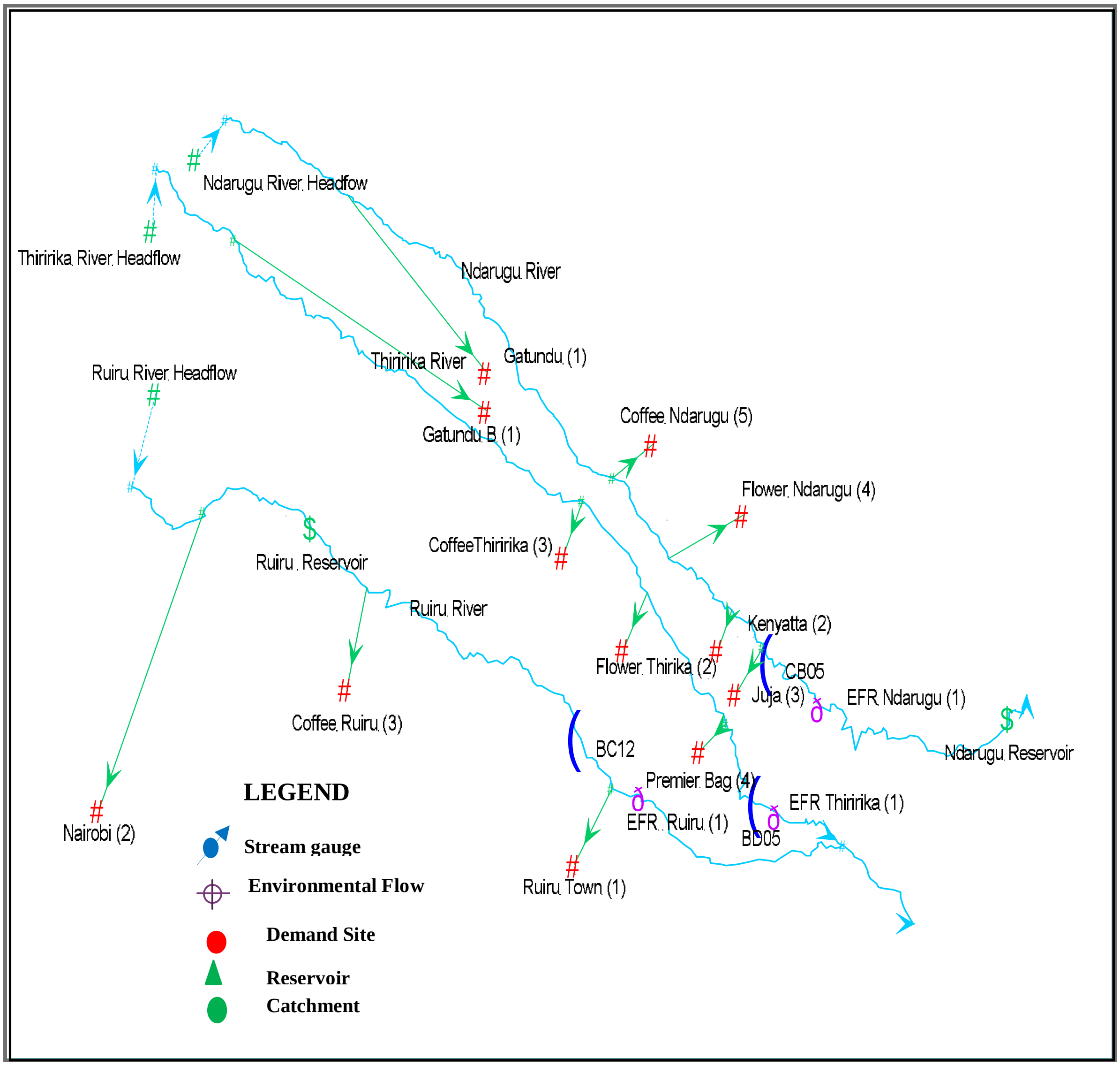


Figure 3.3 Schematic View of Ruiru, Thiririka and Ndarugu Sub-Basin Demand Sites

3.2.3.3 Current Accounts

The current accounts represent the basic definition of the water system as it currently exists. The current accounts are also meant to be the starting year of all the scenarios. In this study, the year 1980 was chosen as the current account year or base year and the entire period set to 1980 to 2008. The current accounts include specifications of supply and demand data for the first year of study on a monthly basis.

3.2.4 Model Calibration and Validation

In this study, the WEAP model was calibrated and validated using stream flow data for 1980 to 1997 as shown in Table 3.6 below.

Table 3.6 Summary of Calibration and Validation Period

Name of River	River Gauging Station	Calibration Period	Validation Period
Ndarugu	3CB05	1980 - 1986	1987 - 1993
Thiririka	3BD05	1980 - 1983	1984 - 1987
Ruiru	3BC12	1980 - 1988	1989 - 1997

As there is no automatic routine for calibration within the WEAP model, changes were implemented and tested manually. Calibration was based primarily on visual comparison of the simulated and observed time series and mean monthly flows (Ronald and Raymond, 1989). The correlation coefficient, a factor to compare the simulated and observed flows was calculated using equation 41:

$$r = \frac{N\sum xy-(\sum x)(\sum y)}{\sqrt{[N\sum x^2-(\sum x)^2][N\sum y^2-(\sum y)^2]}} \tag{41}$$

where N= Number of monthly runoff

$\sum xy$ = Sum of products of paired simulated and observed flows

$\sum x$ = sum of observed flows

$\sum y$= Sum of simulated flows

$\sum x^2$=sum of squared observed flows

$\sum y^2$= sum of squared simulated flows

3.3 Simulation of future water use change scenarios in the river basin

3.3.1 Reference Scenario

The reference scenario is the scenario in which the current situation (1980) is extended to the future (1981 – 2008).

3.3.2 Other Scenarios

A set of scenarios were developed to account for possible changes in the evolution of the water demands (Table 3.7).

Table 3.7 Summary of scenario analysis

No	Description of the scenario	Implications
1	Reference Scenario	This is a scenario in which the population growth rate is continuing at 1969 – 1979 growth rate and improved irrigation efficiency. No major changes are imposed in this scenario.
2	High population growth rate	Increase in population implies an increase in water demand and hence increase in supply
3	A situation where the area under irrigation is reduced by a half	A reduction in area under irrigation by half means water demand for agriculture is reduced by half hence increase the water supply for domestic use
4	A reservoir is added along the river	A reservoir of 19 m^3 was put along Ruiru and Ndarugu rivers. This is to increase the water supplied to demand sites hence reduce the unmet demand.
5	Environmental flow requirement	Water is apportioned to within a river to cater for the ecosystem. Unmet demand for the demand sites is high
6	Irrigation water quality constraint	Water quality constraint at agriculture demand site is by pegged by water quality requirement for irrigation

3.3.3 Water Year Method

The Water Year Method requires data for defining standard types of water years (Table 3.8 and Table 3.9) as well as defining the sequence of those years for a given set of scenarios (Water Year Sequence). A water year type characterizes the hydrological conditions over a period of a year. The five types that WEAP uses are Normal, Very Wet, Wet, Dry and Very Dry. The years are divided into five broad categories based on relative amount of surface water inflow. To define each non-Normal water year type (Very Dry, Dry, Wet and Very Wet) the amount of water flowing into the system in that year relative to a Normal year is specified. For example, if a wet year has 25% more than a Normal year, a coefficient of 1.25 is entered. If a dry year has 25% less than a Normal year, a coefficient of 0.75 is entered. The years are grouped into five bins (quintiles) and their variations from Normal computed. In the WEAP model a Normal year is designated a coefficient of 1.0. The amount of precipitation from 1980 to 2007 was tabulated. The highest amount of rainfall observed was 1598.8mm in 1977 and the minimum rainfall observed was 359.73mm in 2000. The difference between the highest rainfall and minimum rainfall was 1239.07mm. This difference in rainfall was divided into five quintiles to give 248mm.Therefore, a very wet year ranged from 1598.8mm to (1598.8 - 248) mm and a very dry year ranged from 359.73mm to (359.73+248) mm.

Table 3.8 Water Year Definitions

Water Year Definitions	**Average Annual rainfall(mm)**	**Coefficient**
Very Wet	1351 - 1599	1.50
Wet	1103.5 - 1350	1.25
Normal	855.5 - 1103	1.00
Dry	607.5 - 855	0.75
Very Dry	359 - 607	0.50

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Documentation of major water demands and point pollution in the river basin

4.1.1 Major Water Demand sites in the basin

Major water demand sites were identified during the field visits. The eastings, southings and elevations for the demand sites and their intake points were picked by a Global Positioning System (GPS). The major demand sites identified comprise of institutions, towns and coffee and flower farms. The results have been summarized in Table 4.1.

Table 4.1 Summary of demand sites and their locations

Name of site	Easting(decimal)	Southing(decimal)	Elevation (m.a.s.l)
Jomo Kenyatta University intake	37.0264	1.0831	1472
Jomo Kenyatta University	37.0153	1.0953	1528
Juja intake works	37.0369	1.0900	1470
Juja town	37.0139	1.1053	1515
Penta Flowers(Ndarugu)	37.0289	1.0897	1510
Nchengo Estate	36.9886	1.0661	1545
Gatundu town	36.7478	0.9272	2174
Gatundu intake works (Ndarugu)	36.7711	0.8994	2057
Christine Farm(Thiririka)	37.0047	1.1039	1520
Penta Flowers(Thiririka)	37.0003	1.0912	1520
Gatundu intake works (Thiririka)	36.7478	0.9272	2170
Ruiru intake works	36.9647	1.1461	1510
Ruiru town	36.9647	1.1481	1542
Ruiru Dam	36.7558	1.0472	1940
Sasini Tea and Coffee	36.8508	1.0764	1928
Benifa Coffee	37.0228	1.0819	1478

4.1.2 Point pollution along Ruiru, Thiririka and Ndarugu sub-basins

Water quality was assessed based on the Biochemical Oxygen Demand (BOD), total suspended solids, total dissolved solids, electrical conductivity, chlorides, turbidity and copper concentration. BOD is a widely used environmental performance indicator that determines the strength or concentration of biodegradable pollutants in water bodies. Figures 4.1 and 4.2 show the levels of BOD_5, TSS, TDS, EC, Chloride and Copper in Ndarugu river water at Kamwangi (upstream) and Juja Farm (downstream) during the dry and wet season respectively. There was a higher values of BOD_5, TSS, TDS, EC and Chloride for downstream than upstream of the rivers for water qualities collected in the dry season. Copper was not detectable for both upstream and downstream of the rivers (Figure 4.1, Figure A.6.1, Figure A.6.3 and Table A.6.1). During the wet season, the trend was the same with an increase in BOD_5, TSS, TDS, EC and Chloride concentration (Figure 4.2, Figure A.6.2, Figure A.6.4 and Table A.6.2). The increase in BOD_5 concentrations and high value of total dissolved solids is a result of increased contribution of pollutants from surface run off, organic effluent discharges from factories and fertilizers pollutants into the rivers. The increase in total suspended solids is a result of silt deposition from quarry mining, industrial waste and sewage effluent into the rivers. The turbidity generally increased downstream along the rivers (Figure 4.3). This is an indication of the numerous inputs of urban waste water and agricultural runoff. The EC in the three rivers ranged from a minimum of 60.2µS/cm to a maximum of 1732µS/cm during the dry season and 58 µS/cm and 92µS/cm during the rainy season. An EC of less than 250 µS/cm is low salinity (Clemson University, 2001) as shown in Table A.6.5; hence the water quality for the three rivers is good for irrigation. A water quality index (WQI), a weighted average of selected ambient concentrations of pollutants usually linked to water quality and that expresses the overall water quality at a certain location and time, was used to assess the water quality in relation to standards of domestic use (CCME, 2001). The CCME (Canadian Council of Ministers on the Environment) water quality index is given by equation 42:

$$CCMEWQI = 100 - \left(\frac{\sqrt{F_1^2+F_2^2+F_3^2}}{1.732}\right) \quad \text{(CCME, 2001)} \tag{42}$$

Where F_1 represents the percentage of variables that do not meet their objectives at least once during the time period under consideration (failed variables), relative to the total number of variables measured using equation 43:

$$F_1 = \left(\frac{Nunber\ of\ failed\ variables}{Total\ number\ of\ variables}\right) \times 100 \tag{43}$$

F_2 represents the percentage of individual tests that do not meet objectives (failed tests):

$$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) \tag{44}$$

F_3 represents the amount by which failed test values do not meet their objective. F_3 is calculated in three steps:

Step 1: The number of times by which an individual concentration is greater than (or less than when the objective is minimum) the objective is termed an excursion and is expressed as:

$$excursion_i = \left[\frac{FailedTestValue_i}{Objective_j}\right] - 1 \quad (45)$$

For the cases in which the test value must not fall below the objective:

$$excursion_i = \left[\frac{Objective_j}{FailedTestValue_i}\right] - 1 \quad (46)$$

Step 2: The collective amount by which individual tests are out of compliance is calculated by summing the excursions of individual test from their objective and dividing by the total number of tests. This variable, referred to as the normalized sum of excursions, or nse is calculated as:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{Number\ of\ tests} \quad (47)$$

Step 3: F_3 is then calculated by an asymptotic function that scales the normalized sum of the excursions from objective to yield a range between 0 and 100.

$$F_3 = \left(\frac{nse}{0.01nse + 0.01}\right) \quad (48)$$

Using the Water Quality Index (WQI) calculator 1.0(CCME, 2001), a computer software, the water quality index for Ndarugu, Thiririka and Ruiru Rivers were calculated. The water quality index was calculated for water qualities collected during the dry and wet season. The results showed that the water quality index for Kamwangi, Mukini and Ruiru dam during the dry season were 75%, 70% and 82% respectively which means the water quality at the upstream of the three rivers was good (Figure 4.4).

Water qualities collected at the same points in the upstream of the three rivers during the wet season had low water quality index due to high turbidity levels. The water qualities collected in the downstream of the three rivers during the dry season were of fairly good quality but the water quality had reduced due to an increased biochemical oxygen demand. During the wet season, the water quality index was lower and this is attributed to an increase in total suspended solids and turbidity levels (Figure 4.5). The classification of water qualities is summarized in Table A.6.4.

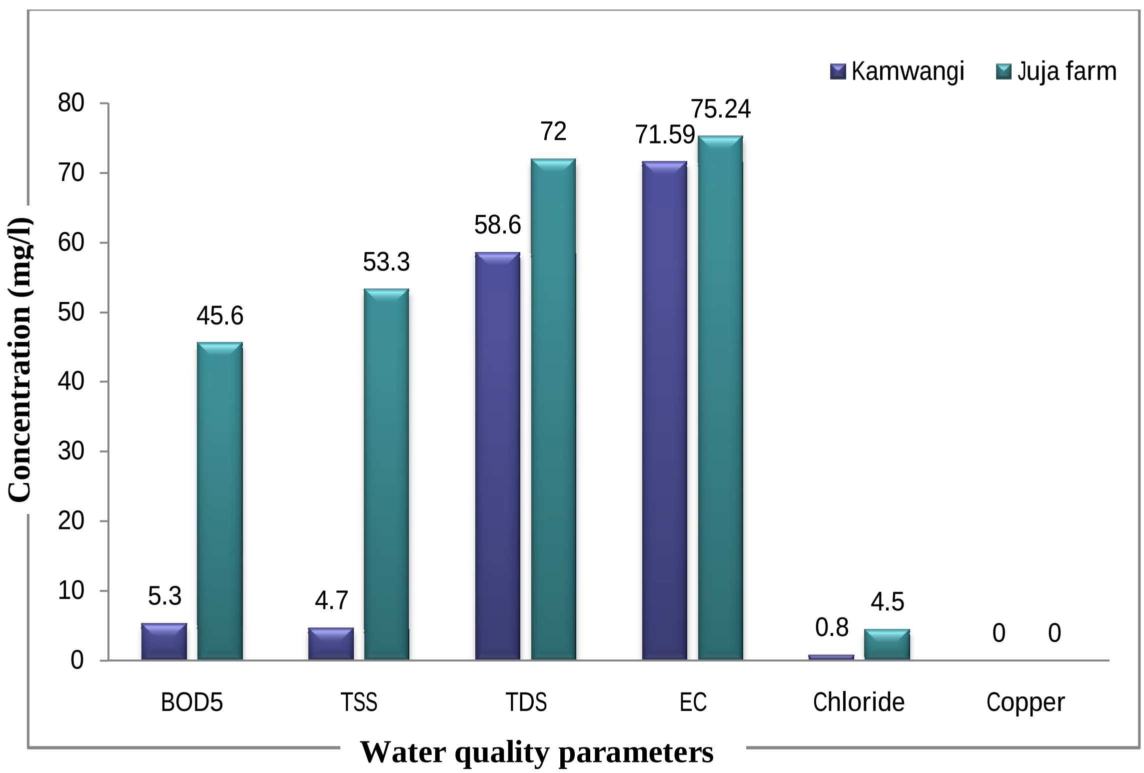


Figure 4.1 Water quality parameters for Ndarugu River during the dry season

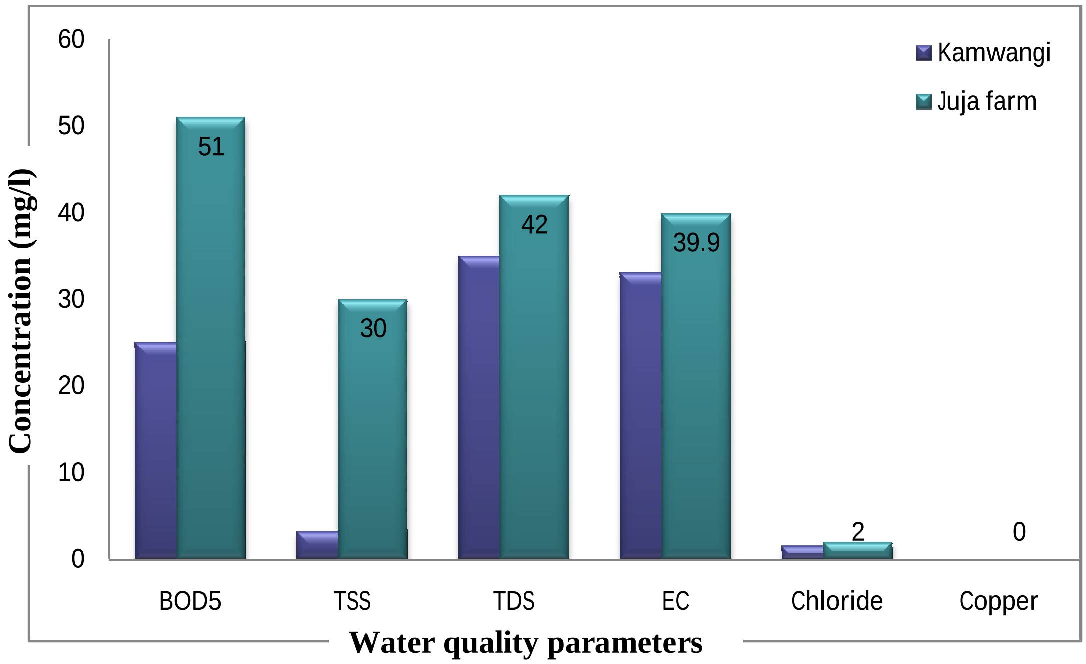


Figure 4.2 Water quality parameters for Ndarugu River during the wet season

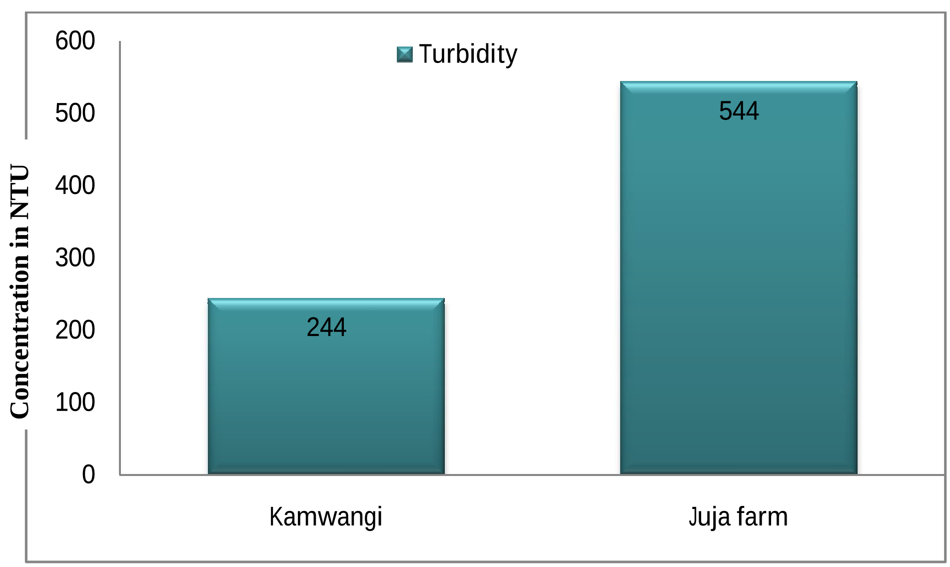


Figure 4.3 Turbidity levels along Ndarugu River during the wet season

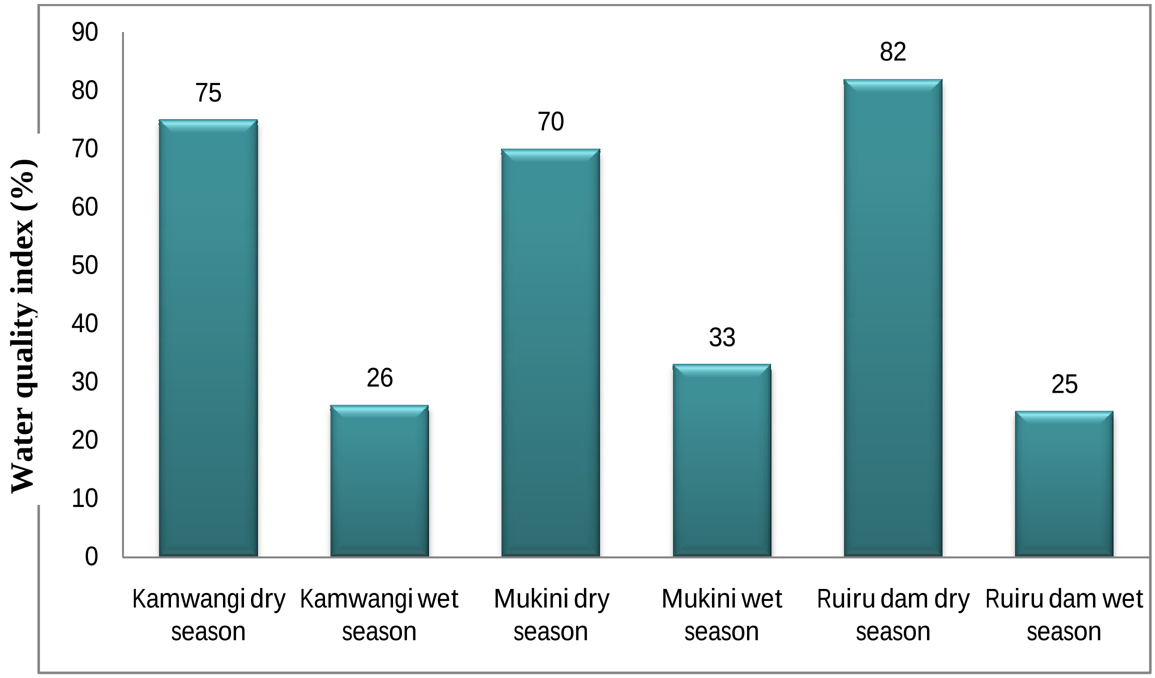


Figure 4.4 Water quality index for water samples collected in the upstream of the three rivers.

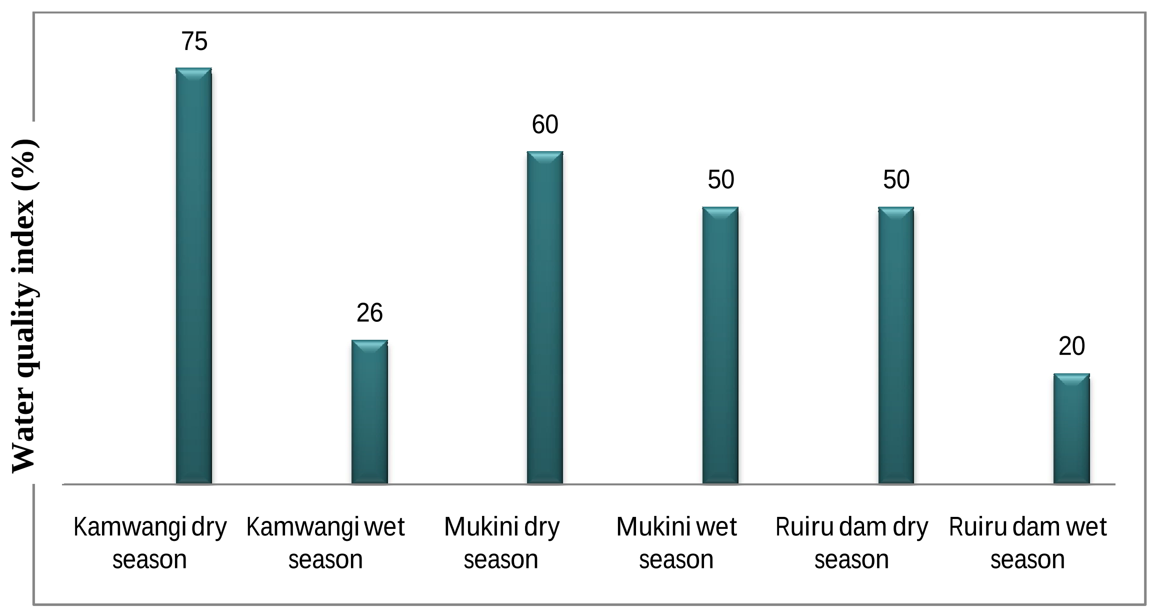
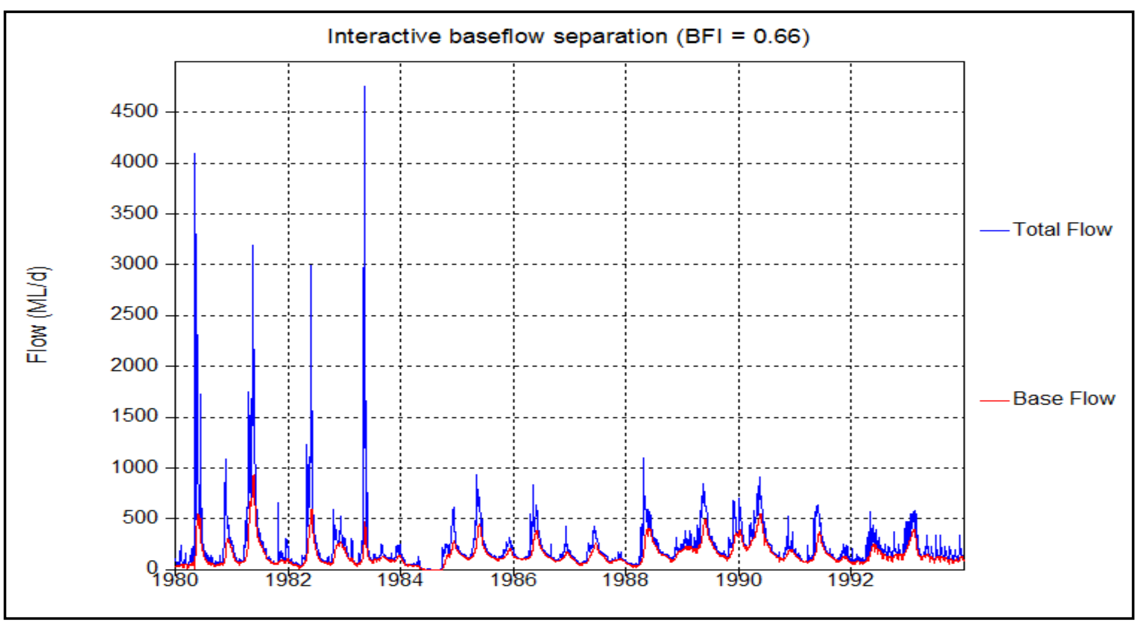


Figure 4.5 Water quality index for water samples collected in the downstream of the three rivers.

4.2 Calibration and Validation of the WEAP Model

4.2.1 Base flow separation

To compare the simulated runoff by the WEAP model with the measured flows, the surface runoff was separated from the stream flow hydrograph. Base flow separation was done using Base Jumper model. Daily discharges in Million litres/day were inputted into the model. The model separated the base flow from the total flows (Table A.7.1, Table A.7.2, Figure 4.6, Figure A.7.1 and Figure A.7.2). The base flow was subtracted from the total flow to give runoff (Figure 4.7, Figure A.8.1 and Figure A.8.2). The base flow index (BFI), which is the ratio of base flow to total stream flow was calculated by the model as 0.66 for 3CB05. The BFI provides a systematic way of assessing the proportion of base flow to the total runoff of a catchment.



Time (days)

Figure 4.6 Baseflow separation for Ndarugu River (3CB05)

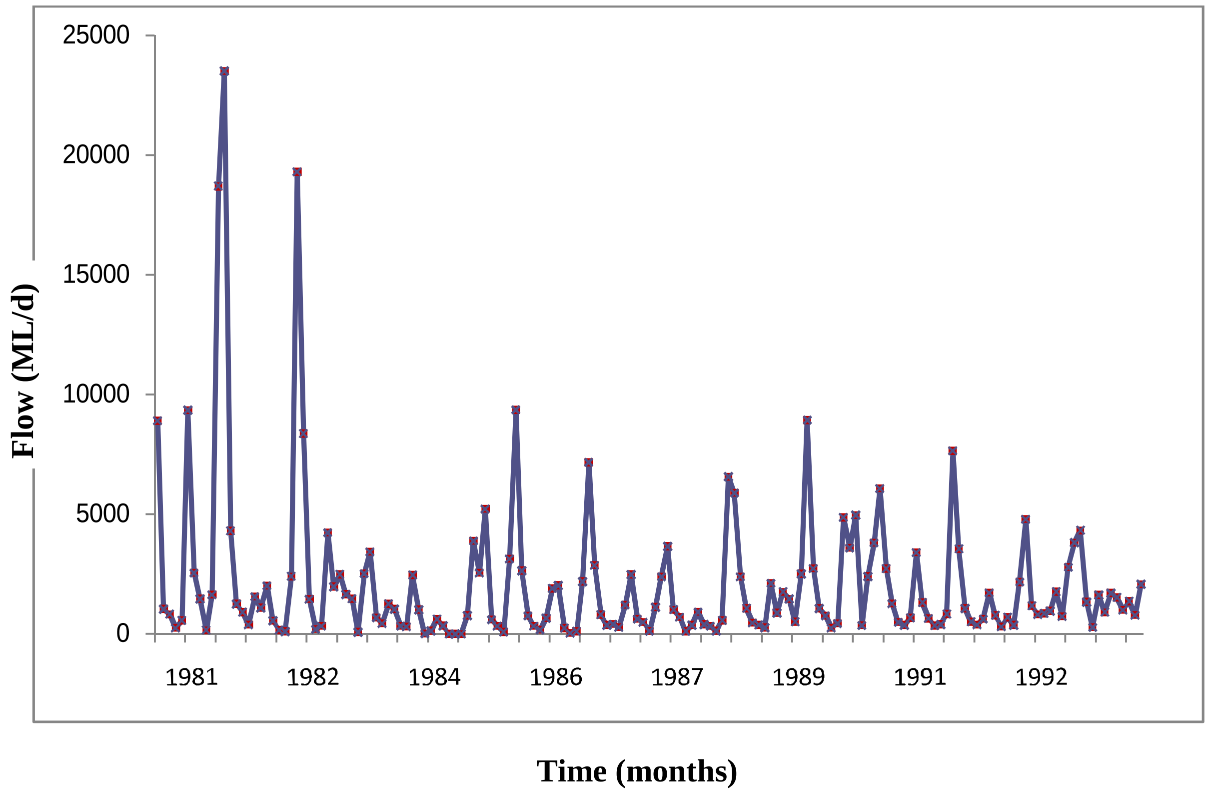


Figure 4.7 Monthly Runoff for Ndarugu River (3CB05)

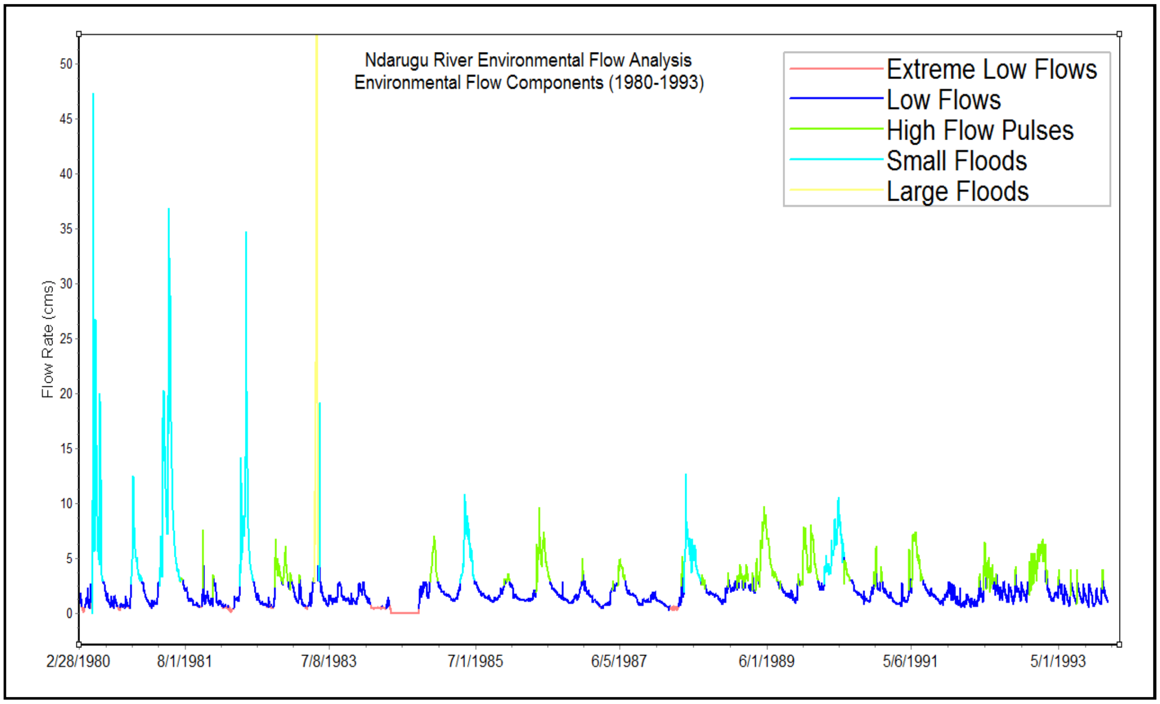
4.2.2 Environmental Flow Analysis

Daily stream flows were inputted into the Indicators of Hydrologic Alteration (IHA). The model calculated five different types of environmental flow requirement components(EFC) i.e. low flows, extreme low flows, high pulses, small floods and large floods (Table 4.2, Figure 4.8, Figure A.9.1 and Figure A.9.2). The IHA model computes the environmental flow components as follows: all the flows that exceeds 75% of the daily flows are classified as high flows; all flows that are below 50% of the daily flows are classified as low flows; an extreme

low flow is defined as an initial low flow below 10% of daily flows for the period; a small flood event is defined as an initial high flow with a peak greater than 2 years return interval event; a large flood event is defined as an initial high flow with a peak flow greater than 10 years return interval period. The monthly low flows is taken as the environmental flow requirement since it provides adequate habitat for organisms, provides drinking water for terrestrial animals, maintains water table in flood plain and enables support of hyporheic organisms. For Ndarugu stream flow data, the model described low flows as ranging from 0.68 m^3/s to 2.94 m^3/s. For Thiririka and Ruiru stream flow data, the low flows were ranging from 0.31m^3/s to 2.11 m^3/s and 0.69 m^3/s to 5.17 m^3/s respectively. The daily minimum low flow for each river was multiplied by 31 days to give the monthly low flows. The monthly low flows that were calculated are 21, 10 and 22 m^3/s for Ndarugu, Thiririka and Ruiru River respectively. These monthly low flows were then inputted into the WEAP model as the environmental flow requirement. Table 4.3 shows a sample results for environmental flow components generated by IHA model.

Table 4.2 Sample results of environmental flow components for Ndarugu River

Date	Flow(m^3/s)	Environmental Flow Component Description
4/20/1983	2.739	low flow
4/21/1983	2.899	low flow
4/22/1983	2.818	low flow
4/23/1983	2.899	low flow
4/24/1983	3.025	high flow pulse
4/25/1983	3.150	high flow pulse
4/26/1983	3.237	high flow pulse
4/27/1983	3.065	high flow pulse
4/28/1983	2.899	low flow
4/29/1983	2.818	low flow
4/30/1983	2.899	low flow
5/3/1983	16.560	large flood
5/4/1983	6.280	large flood
5/21/1983	3.089	small floods
5/22/1983	3.024	small floods



Time (days)

Figure 4.8 Environmental Flow Components for Ndarugu River

4.2.3 Calibration and Validation of WEAP model

Calibration and validation was done by comparing the simulated and measured monthly flows for 3CB05, 3BD05 and 3BC12 stream flow gauges. The parameters that were available for catchment simulation are catchment area, crop coefficients, effective precipitation, evapotranspiration and precipitation. Catchment area, precipitation and effective precipitation are constant. The crop coefficient (K_c) and reference evapotranspiration (ET_o) values were the parameters that were varied until an acceptable value of the correlation coefficient (R^2) was achieved. The parameters that were used for calibration, validation and eventual simulation of scenarios have been summarized in Table 4.3 and Table 4.4. The correlation coefficient (R^2) between the simulated and observed stream flow were assessed for the three gauging stations. For station 3BC12, an R^2 of 0.803 was obtained during calibration (Figure 4.9). The simulated and observed mean monthly flow at the gauging station differed by 4.28 m^3/s (Table 4.5). During the validation process, station 3BC12 had R^2 of 0.811 (Figure 4.10). The difference between the observed mean flow at gauging station 3BC12 and the measured mean flow at gauging station 3BC12 was 3.3m^3/s. Other results have been shown in Table 4.6, Figure A.10.1, Figure A.10.2, Figure A.10.3 and Figure A.10.4. The correlation coefficients (R^2) for station 3BD05 and 3CB05 for calibration and validation was relatively high. The difference between the observed and simulated mean flows was 1.23m^3/s for station 3CB05. For station 3BD05, the difference between the observed and simulated mean monthly flow was comparable during the validation process but the difference was extremely high during the calibration process.

Table 4.3 Summary of crop factors used for calibration

Cropping type	Crop factors
Forest	0.90
Rain fed agriculture	1.15
Irrigated agriculture	1.10
Grassland	0.95

Table 4.4 Summary of Monthly Daily Reference Evapotranspiration (mm/day)

Month	January	February	March	April	May	June
ETo	4.89	5.36	5.12	4.16	3.68	3.32
Month	July	August	September	October	November	December
ETo	3.04	3.21	4.27	4.67	4.18	4.40

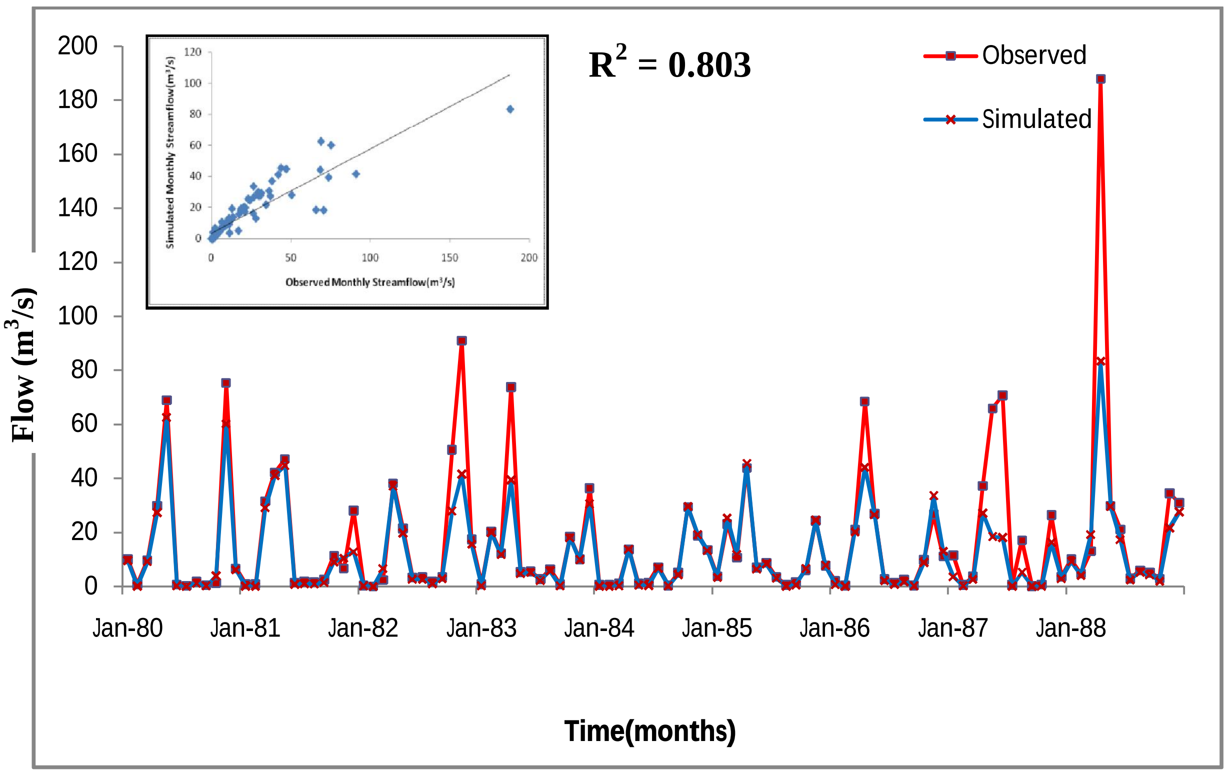


Figure 4.9 Observed and simulated stream flow for Ruiru River at station 3BC12 with scatter plot showing the correlations during calibration

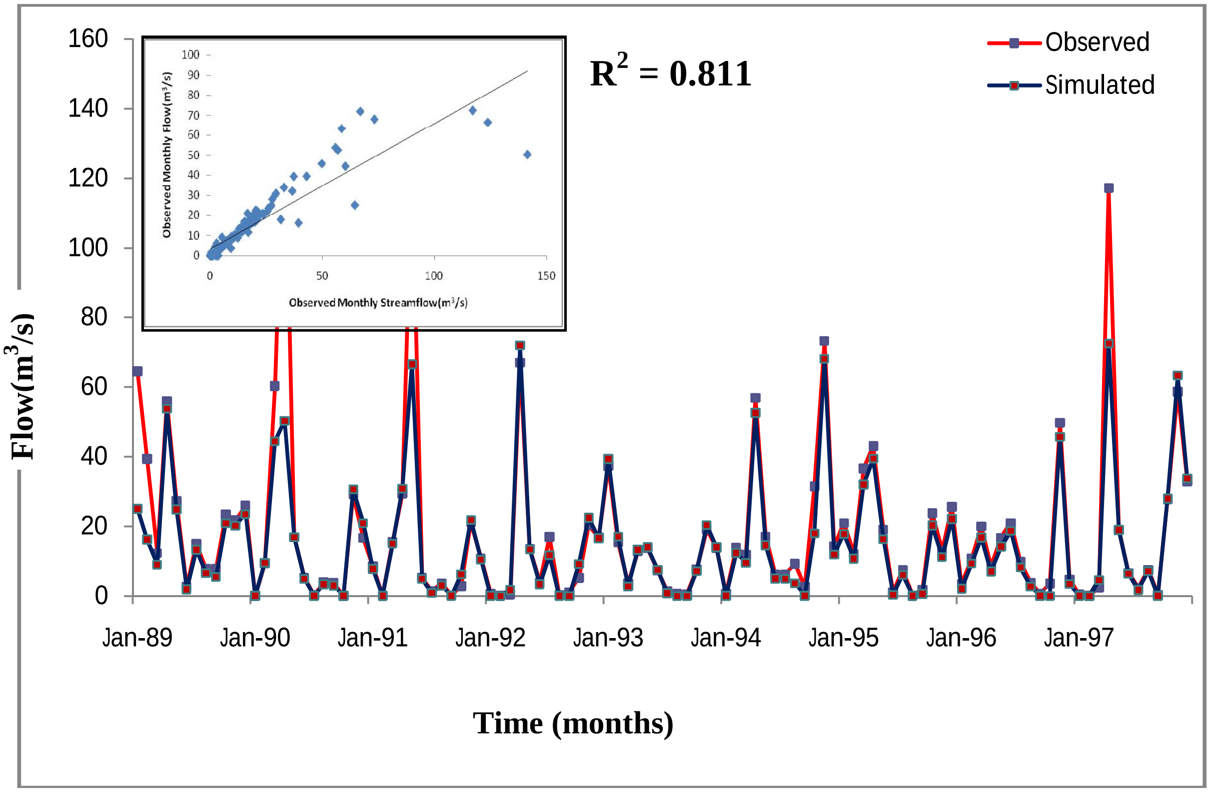


Figure 4.10 Observed and simulated monthly stream flow for Ruiru River at station 3BC12 with scatter plot showing the correlations during validation

Table 4.5 Comparison of the observed and simulated mean flow during calibration period at various gauging stations

Period	**River Gauging Station**	**River**	**Drainage Area(Km^2)**	**Mean Flow(m^3/s)**		**Correlation Coefficient (R^2)**
				Observed	**Simulated**	
1980 - 1986	3CB05	Ndarugu	395	9.28	7.28	0.80
1980 - 1983	3BD05	Thiririka	328	16.78	7.99	0.85
1980 - 1988	3BC12	Ruiru	476	16.68	12.40	0.80

Table 4.6 Comparison of the observed and simulated mean flow during validation period at various gauging stations

Period	River Gauging Station	River	Drainage Area(Km^2)	Mean Flow(m^{3}/s)		Correlation Coefficient (R^2)
				Observed	Simulated	
1987 - 1993	3CB05	Ndarugu	395	10.20	8.97	0.80
1984 - 1987	3BD05	Thiririka	328	7.80	6.56	0.88
1989 - 1997	3BC12	Ruiru	476	18.20	14.90	0.81

The relationship between monthly simulated and observed flows indicated a high correlation whose coefficients varied from 0.801 to 0.849 during the calibration period and varied from 0.804 to 0.88 during the validation period. These statistical results indicate good model performance in reproducing the stream flow trend. In general, the results indicated that WEAP model can be able to reproduce the hydrological dynamic of the basin as shown in the calibration and validation process. The simulated flows represented 74% to 87% of the measured flows except for 3BD05 during the calibration period that had a higher measured mean flow than the simulated. This could have been attributed to human error in recording the daily stream flow data. In practice, the model calibration and validation can be viewed as a systematic analysis of errors or differences between model prediction and field observation. The purpose of validation is to assure that the calibrated model properly assesses all variables and conditions which can affect model results, and demonstrate the ability to predict field observations for period separate from calibration period.

4.3 Simulation of future water use change scenarios in the river basin

4.3.1 Scenario 1: Reference or the business as usual scenario

The annual water demand for agriculture and domestic use in Ruiru, Thiririka and Ndarugu sub-basins was 14.8 MCM and 18.1 MCM in 1980 respectively. The annual water demand for domestic use rose to 45.8 MCM in 2008 (Table 4.7). The average population growth rate used was 4.7% for Nairobi and 2.8% for the rest of the demand sites based on 1989 population census. The amount of water delivered for domestic purposes were 9.5 MCM in 1980 and rose to 24 MCM in 2008 (Figure 4.15 and Table A.11.1). During this scenario, the highest amount of water supplied into all the demand sites was in the month of April (Figure A.11.1). This is because there are a lot of rains during this period resulting in high river flows. It was also observed that the lowest amount of water supplied to demand sites was in the month of September for all the demand sites. This is due to low flows as a result of less or no rains during period. The demand site coverage for Coffee Ruiru, Flower Ndarugu, Flower Thiririka and Gatundu was 100% i.e. all the water requirement was met between January and December. The demand site coverage for Coffee Ndarugu ranged between 11.4% and 45.1% and the coverage was highest in April and lowest in September. In Coffee Thiririka, Juja, Nairobi, Premier Bag and Ruiru town, the demand site coverage varied from 14.6% to 50.8% with the highest demand site coverage in April and the lowest demand site coverage in September. The unmet demand for domestic use was 4.39 MCM in 1980 and rose to 11.88 MCM in 2008 (Figure 4.16 and Table A.11.2). All the water demand for Gatundu and Jomo Kenyatta University were met in all years between 1980 and

2008. For Gatundu B, all the water demand was met for the year 1988 and 1989. The lowest unmet water demand for Gatundu B and Juja was in 1998 with 0.578 MCM and 0.149 MCM respectively. All the water demand for Nairobi and Ruiru town was met in 2007. The unmet demand for Nairobi was highest in 1996 (Figure 4.11 and Figure 4.12). This was due to declined mean discharges as a result of low rainfall in 1996 as shown in Figure 4.13. The stream flow data for 3CB05 were offset by -37 to read data for future years from 2018 to 2030. The stream flow data for 3BD05 were offset by -43 to read data from 2024 to 2030 and the stream flow data for 3BC12 were offset by -33 to read data from 2014 to 2030. The years and time steps of the WEAP model were changed to read 1980 to 2030 to analyze data for future scenarios. During the offset years of 2014 to 2030, the unmet demand for Nairobi increased from 19 MCM in 2014 to 39.66 MCM in 2030, an increase of 20.66 MCM in a period of 16 years (Figure 4.14). The unmet demand for Ruiru town during the offset period increased from 7.49 MCM to 11.65 MCM in 2030, an increase of 4.16 MCM. This means as we approach the year 2030, proper strategies have to be put in place so that the unmet demand can be met.

Table 4.7 Annual Water Demand for the Study Area for Scenario 1 in MCM

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Coffee Ndarugu	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Coffee Ruiru	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Coffee Thiririka	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Gatundu	4.3	4.8	5.3	6.0	6.7	7.4	8.3	9.3
Gatundu B	4.3	4.8	5.3	6.0	6.7	7.4	8.3	9.3
Juja	2.6	3.0	3.3	3.7	4.1	4.6	5.1	5.7
Jomo Kenyatta University	0	0.1	0.1	0.2	0.2	0.4	0.5	0.8
Nairobi	4.0	4.8	5.8	6.9	8.3	10	12	14.4
Ruiru Town	2.9	3.3	3.7	4.1	4.6	5.1	5.7	6.3
Others	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

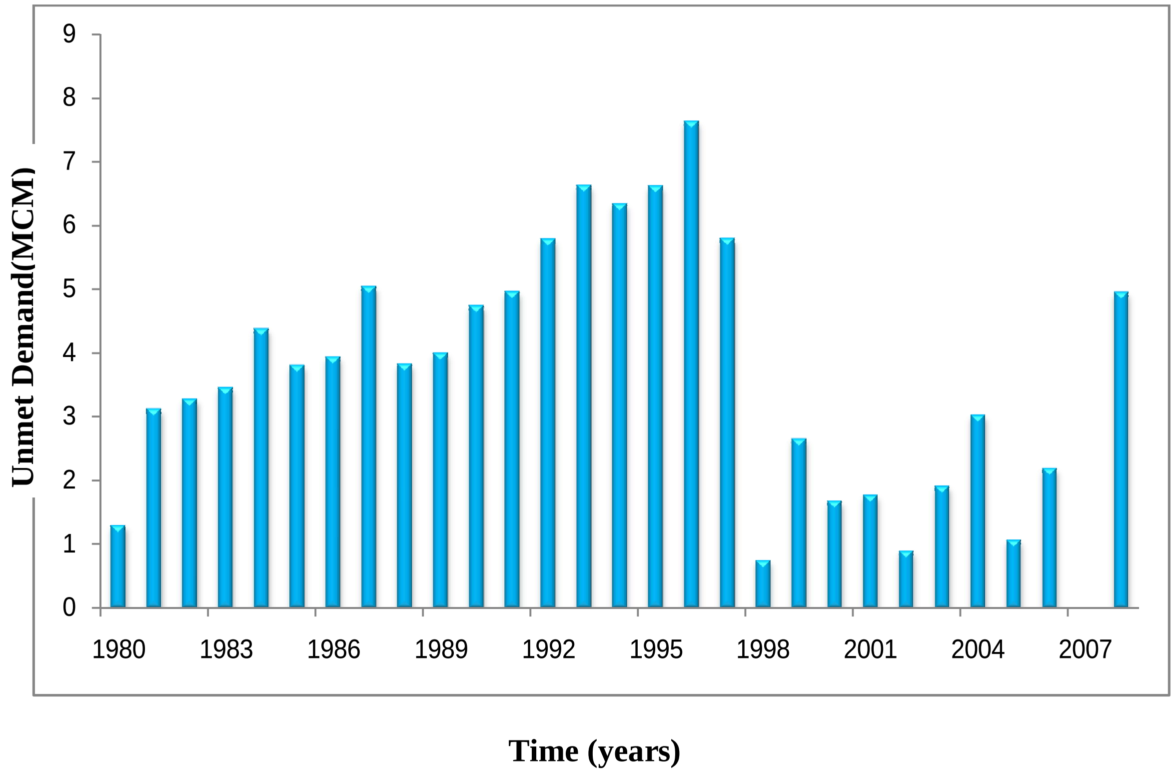
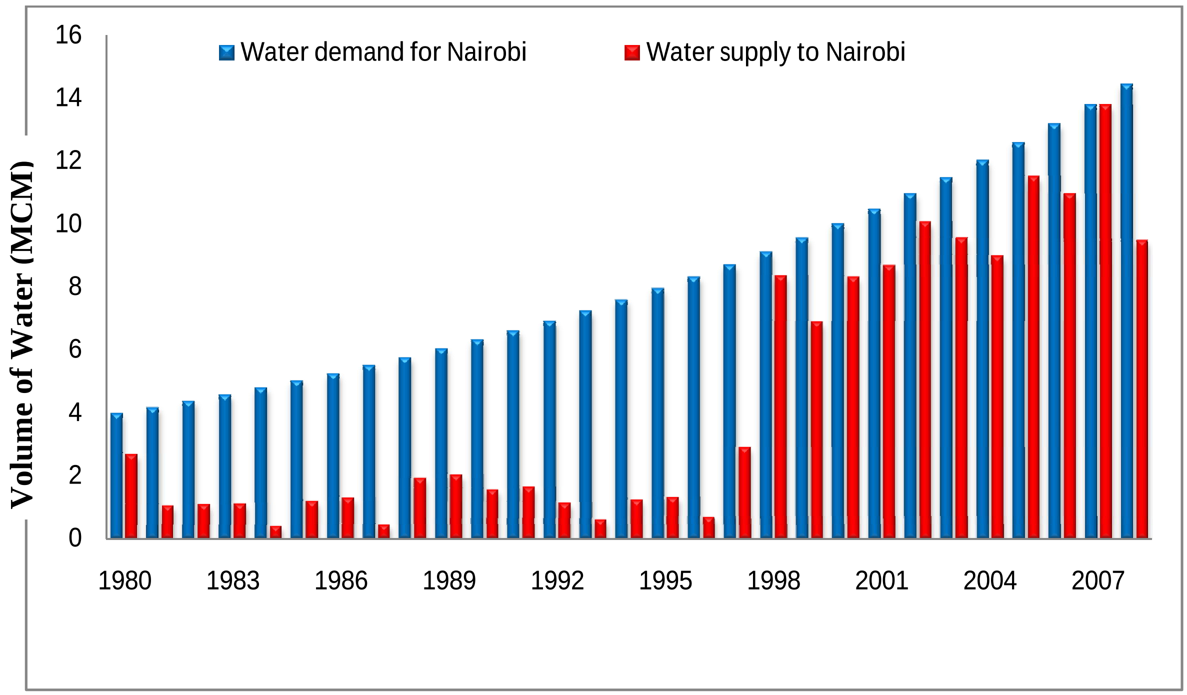


Figure 4.11 Unmet Demand for Nairobi in Scenario 1



Time (years)

Figure 4.12 Water demand and supply for Nairobi

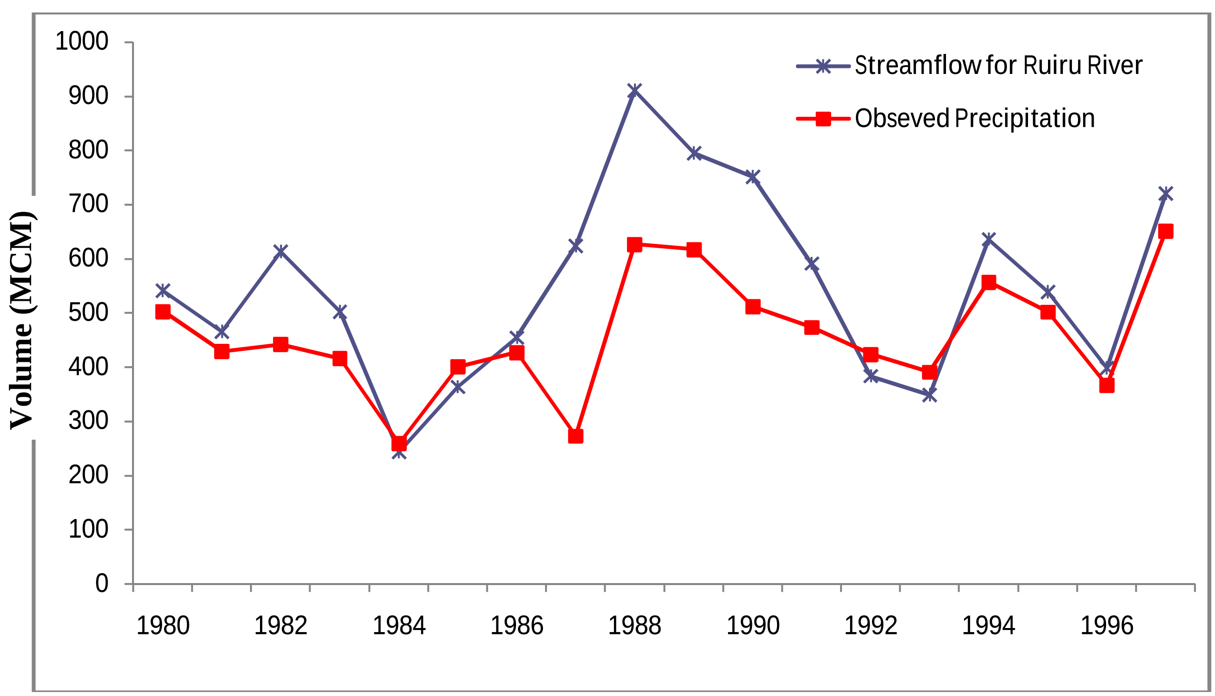


Figure 4.13 Comparison of Runoff and stream flow for Ruiru River (3BC12)

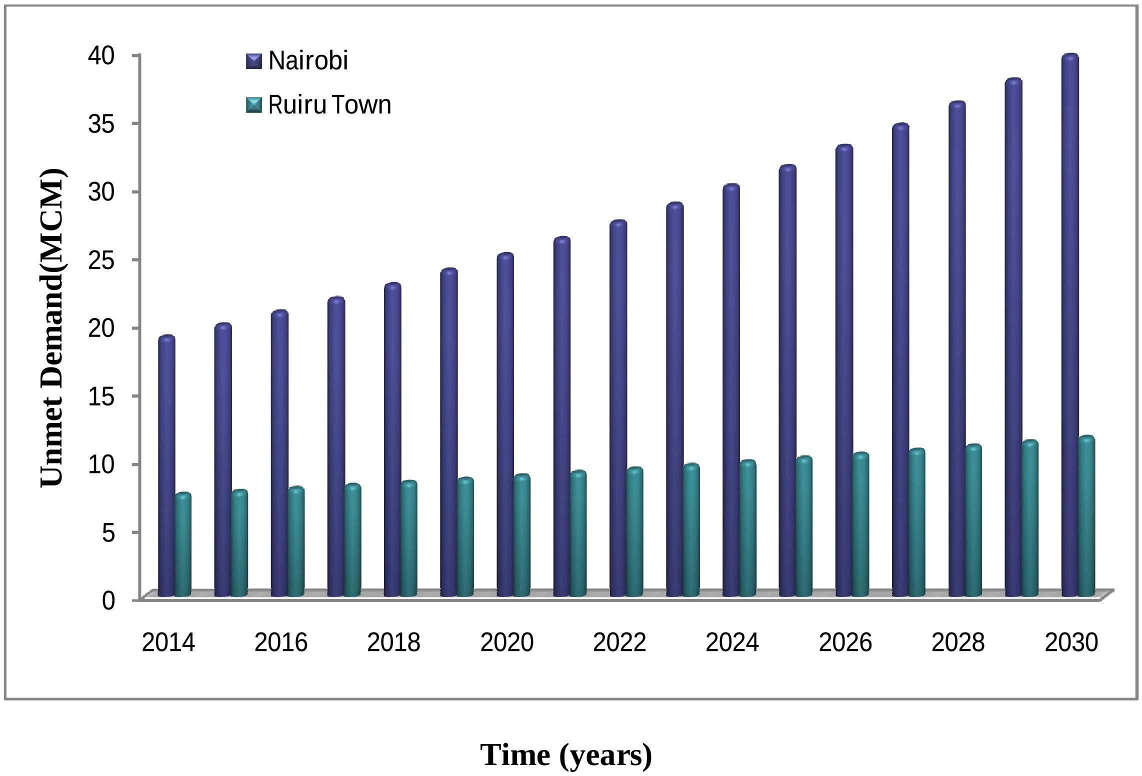
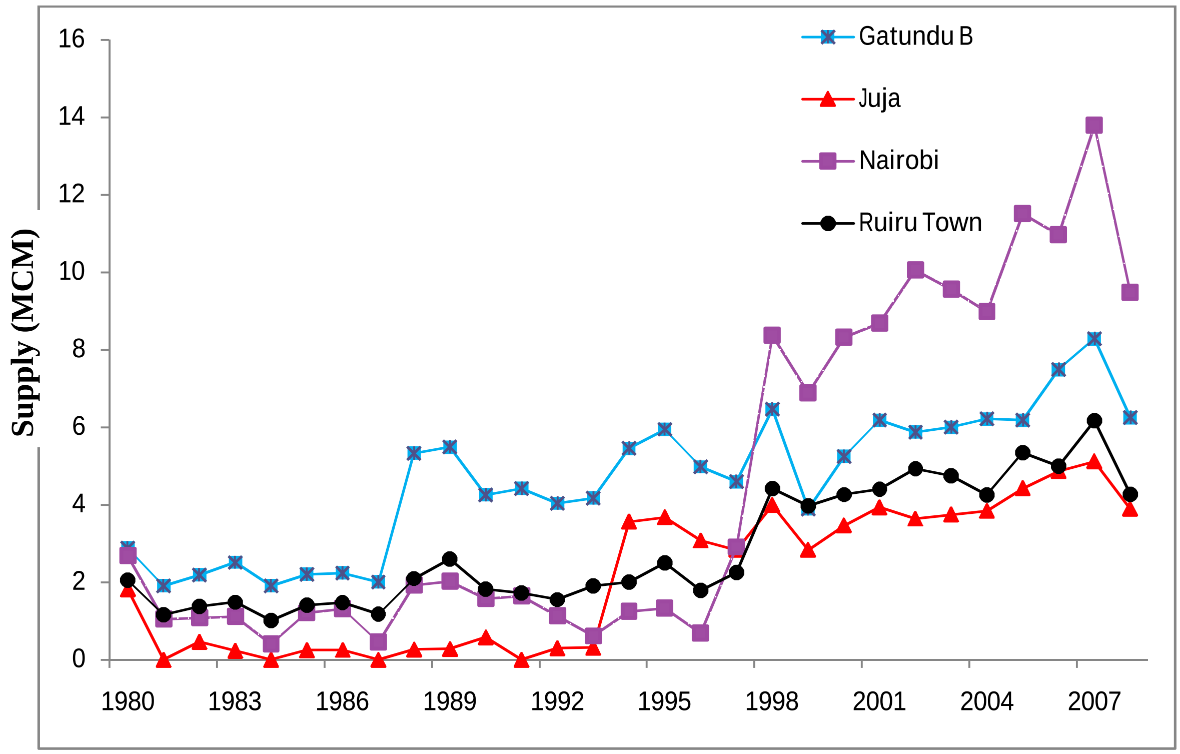
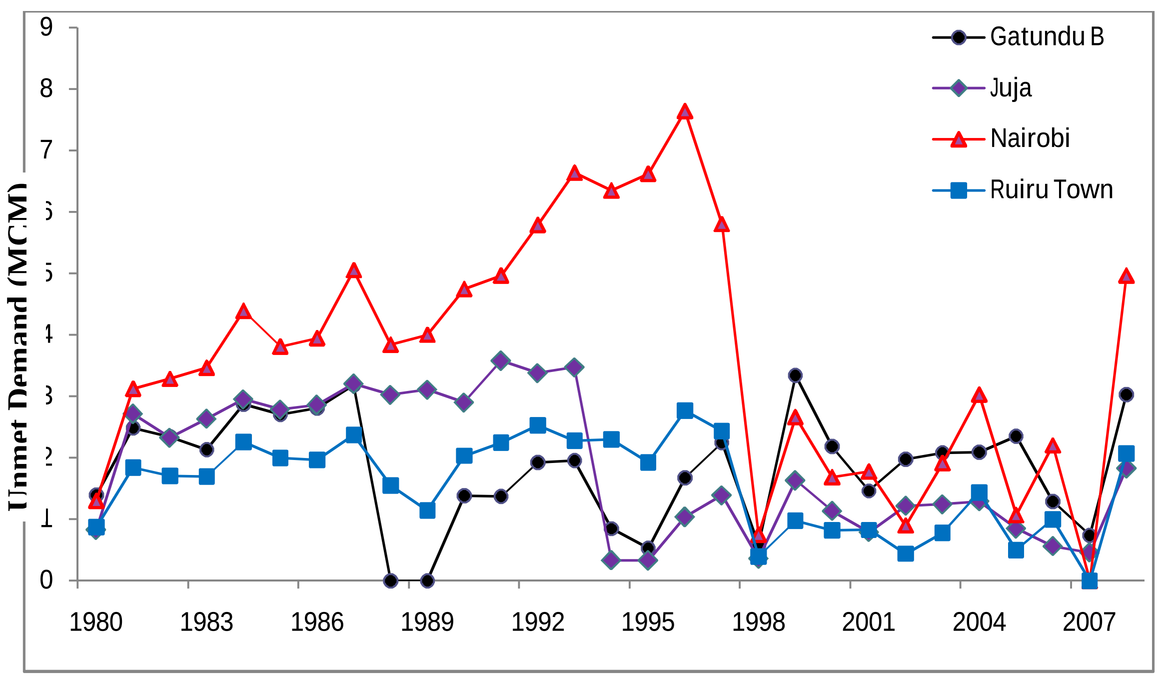


Figure 4.14 Unmet demand for Nairobi and Ruiru during the offset years (2014 – 2030)



Time (years)

Figure 4.15 Supply Delivered for Scenario 1



Time (years)

Figure 4.16 Unmet Demand for Scenario 1

4.3.2 Scenario 2: High Population Growth Scenario

When the population growth rate is increased from the current growth rate to 7 % (GOK, 2009b), the water demand for domestic use was 18.1 MCM in 1980 and rose to 121.4 MCM in 2008, 75.6 MCM above the water demand in reference scenario (Table A.11.3). There was an increase in water supply to domestic demand sites in this scenario compared to reference scenario as shown in Figure 4.17. The supply delivered for domestic use was 13.1 MCM in 1980 and rose to 85.7 MCM in 2008 (Table A.11.4). All water demand for Gatundu and Jomo Kenyatta University were fully met i.e. 4.3 MCM in 1980 and 29.3 MCM in 2008. During this scenario, the highest amount of water supplied to demand sites was in the month of April while the lowest amount of water supplied was in the month of September. However, in Coffee Ndarugu, the same amount of water was supplied in April, May, October, November and December as in reference scenario but slightly lower in the months of January to March and June to September. In Coffee Thiririka, the highest supply was made in April and lowest supply was made in September. However, in the months of February, April, May and November, the supply made to Coffee Thiririka was the same as in reference scenario but slightly low supply in January, March, June, July, August and October to December. The case for Nairobi water supply was different. There was an increase in water supply to Nairobi in all the months from January to December. This is probably due to the increase in population as result of increased population growth in this scenario. For Ruiru town, the water supply trend was the same as in Nairobi. There was an increase in water supply to Ruiru town for all the months from January to December. In fact, the water supply to Ruiru town doubled compared to water supply in reference scenario. The unmet demand was high in this scenario compared to reference scenario (Figure 4.18). The unmet water demand for domestic use was 4.4 MCM in 1980 and rose to 35.7 MCM in 2008 (Table A.11.5).

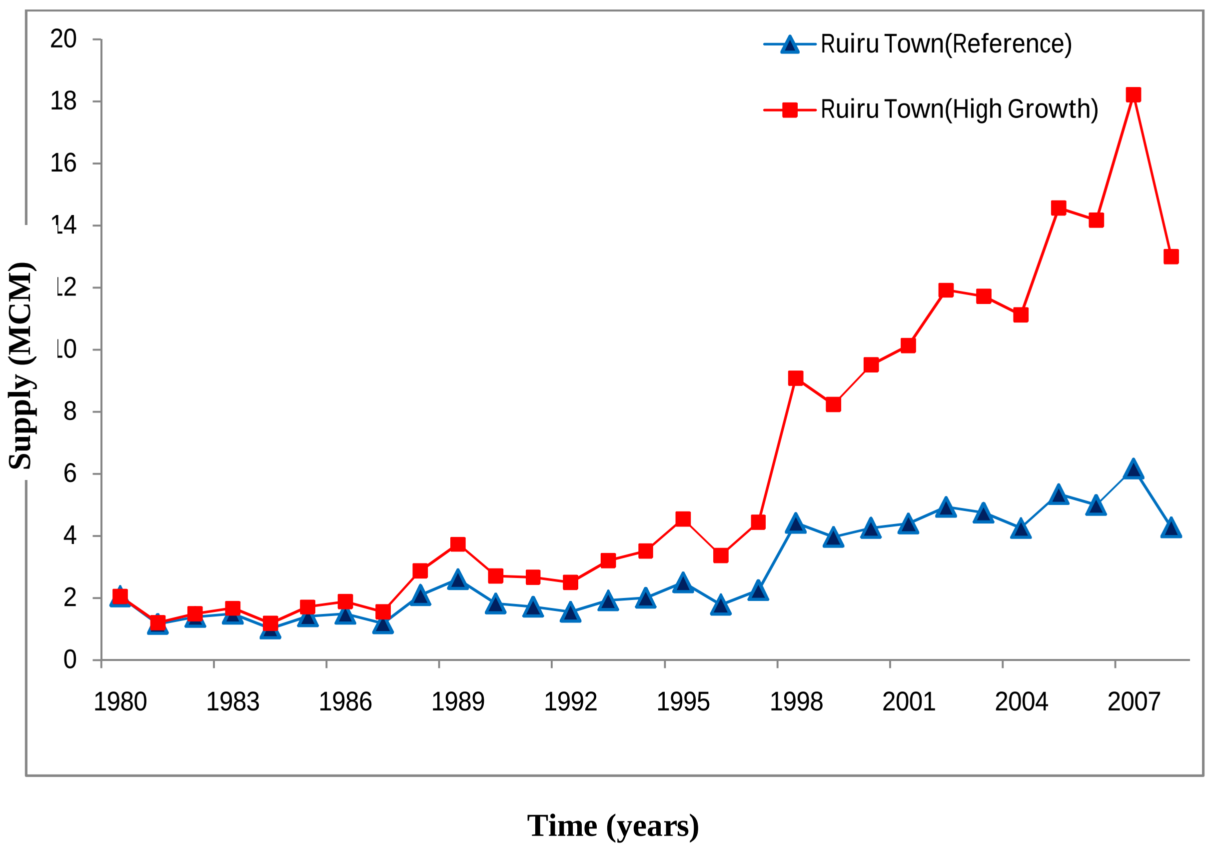


Figure 4.17 Supply Delivered for Scenario 2

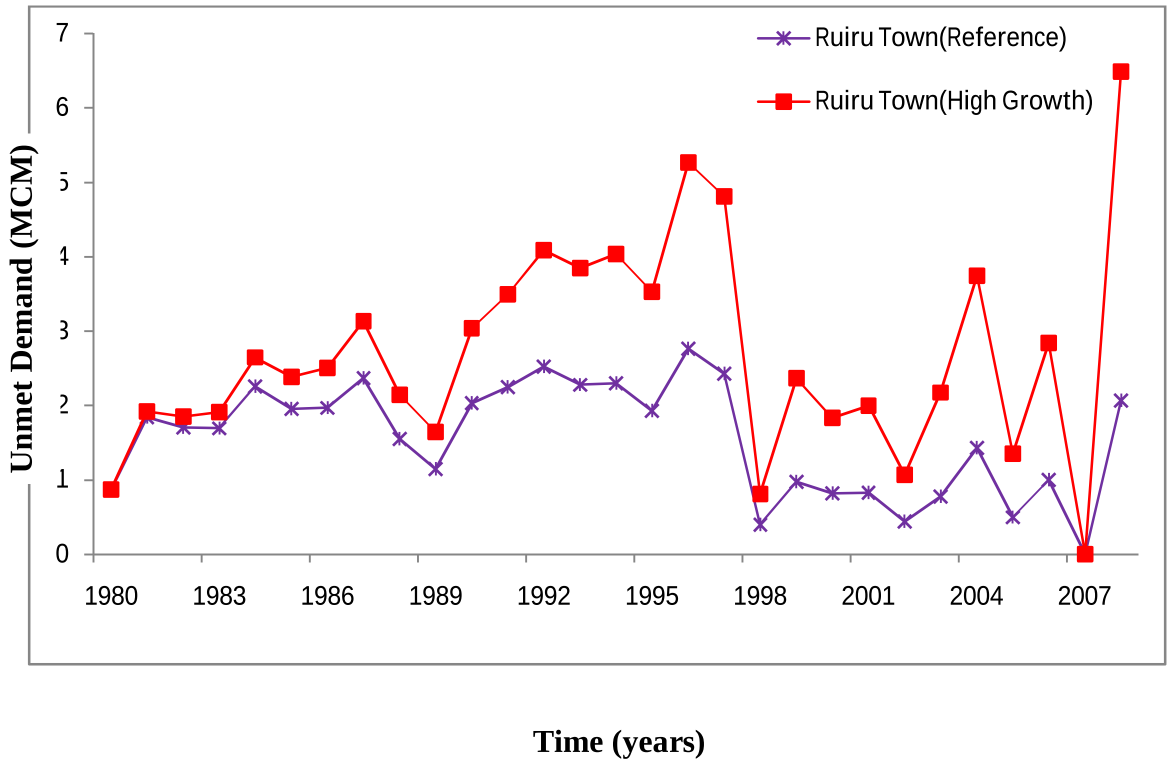


Figure 4.18 Unmet Demand for Scenario 2

4.3.3 Scenario 3: Area under Irrigation is reduced by half

When the area under irrigation is reduced by half, the water demand for agriculture reduces by half (Table A.11.6). The amount of water supplied to agriculture was 12.7 MCM in 1980 and reduced to 6.5 MCM in 1981 but varied all through to 2008 (Table A.11.7). The water supply was lower than in reference scenario for agriculture demand sites (Figure 4.19). The water supply to agriculture demand sites reduced by almost a half as result of reduced acreage in this scenario. For Nairobi, Ruiru, Gatundu and Juja, the water supply was the same as in reference scenario. Reducing the acreage under irrigation, does not affect the water supply to domestic demand sites. Only in Premier Bag where there was slight increase of water supply in the months of June, July and August while the other months had a water supply the same as in reference scenario. By reducing the area under irrigation by half, the unmet demand for agriculture reduced considerably (Figure 4.20). The unmet demand for Nairobi, Ruiru, Juja and Gatundu was the same as in reference scenario. The unmet demand for Premier Bag was the same as in reference scenario except for the year 1999, 2000 and 2008 where there was reduction of 7588, 7797 and 9672 m^3 of unmet demand respectively. All the water demand for Jomo Kenyatta University was met in this scenario. The unmet demand for domestic demand sites remained as in reference scenario (Table A.11.8).

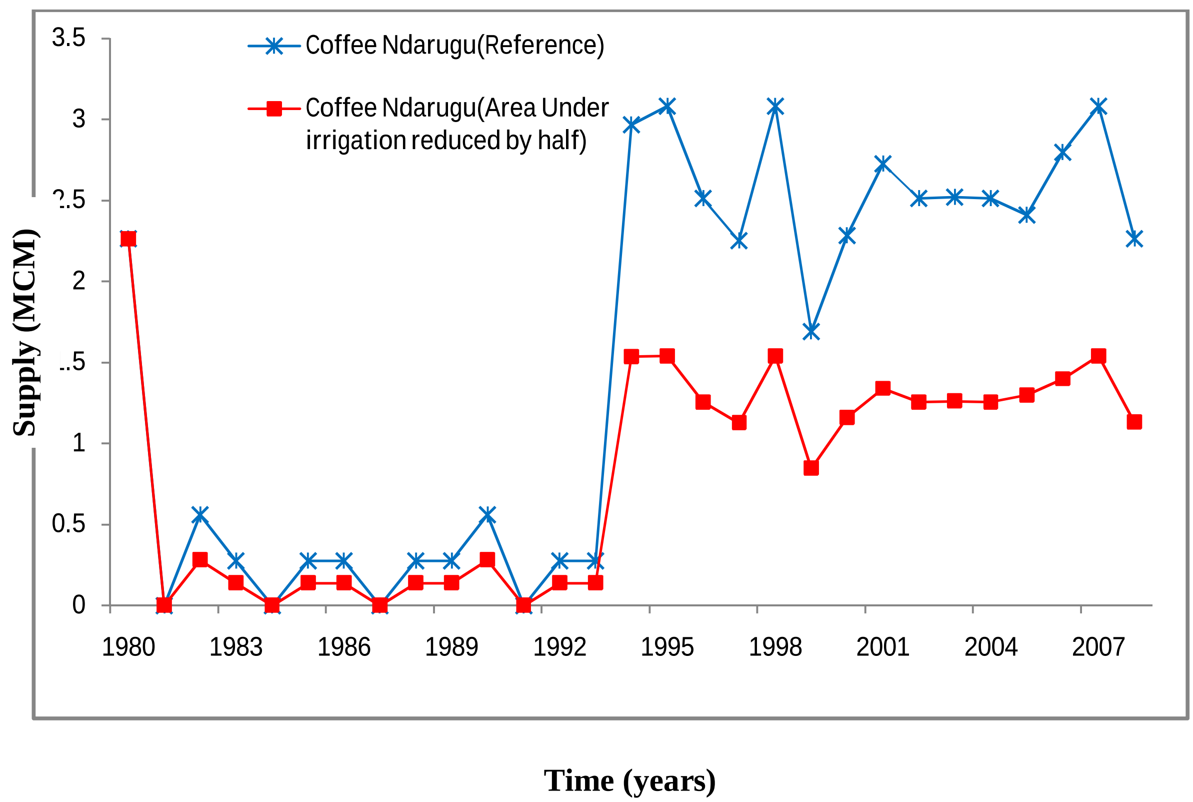


Figure 4.19 Supply Delivered for Scenario 3

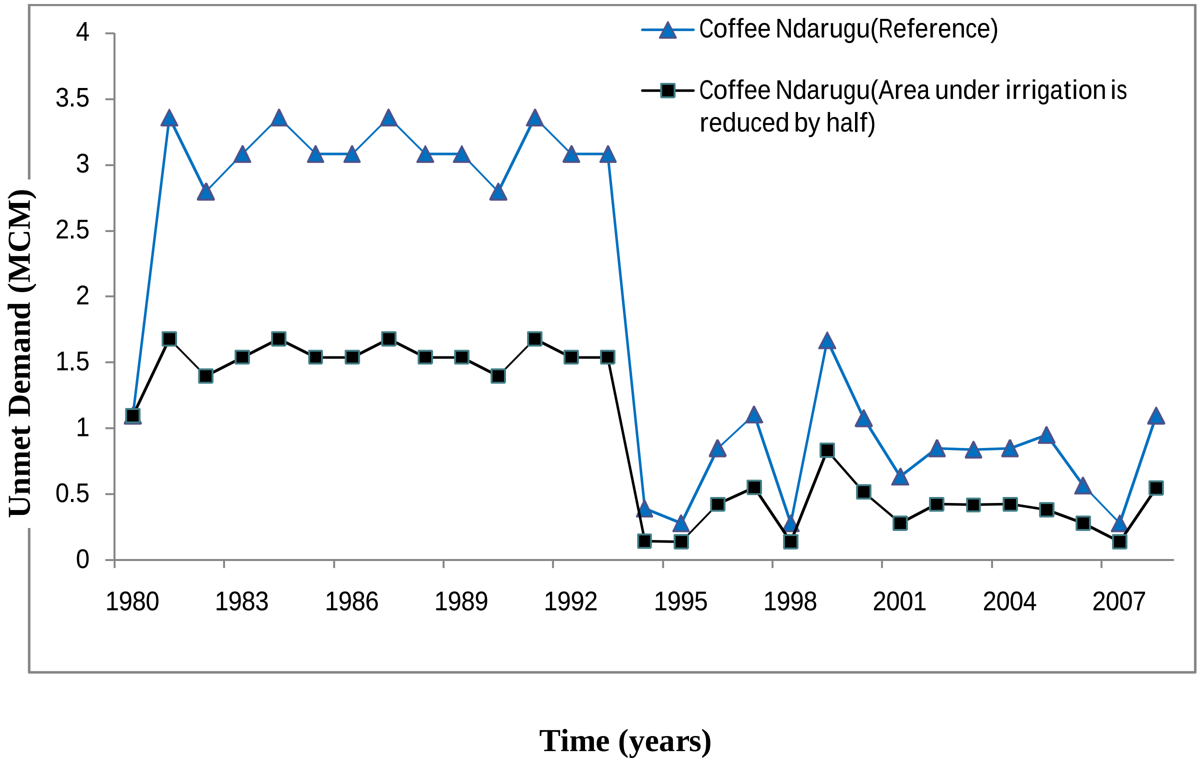


Figure 4.20 Unmet Demand for Scenario 3

4.3.4 Scenario 4: Reservoir added along Ruiru River

Two dams were created in this scenario. Ruiru A dam with 19 MCM (as proposed by JICA in 1992) was created along Ruiru River, 2 km from the existing Ruiru dam. Ndarugu dam with 19MCM was created along Ndarugu River just downstream of confluence of Komu and Ndarugu Rivers as shown previously in Figure 2.4. These are proposed dams by the Government to increase water supply in the sub basin (JICA, 1992). For Nairobi town, the water supply was the same as in reference scenario in the months of January, March, July, September and October but there was an increase in water supply to Nairobi in this scenario in the months of February, May, June, August, November and December. For Ruiru town which has a direct transmission link from Ruiru Reservoir, there was a general increase in water supply from January to December. This is shown in Figure 4.21. The unmet demand for Ruiru town was much lower compared to reference scenario (See Figure 4.22). All the water demand for Ruiru town was met from 1998 to 2008. This was attributed to the 1997 – 1998 Elnino rains that hit several parts of the country (Figure 4.23). The dam was filled to full capacity of 19 MCM and the supply of water to Ruiru town was almost doubled and reduced the unmet demand to zero. During the period of 1980 to 1996, the reservoir was full in the months of April and May but in the months of January to February and July to December, less or no water was collected. The demand priority for Ruiru town was set to 1, Nairobi was set to 2 and Coffee Ruiru was set to 3 as shown in Table 4.8.

Table 4.8: Summary of demand priorities

River Basin	**Demand Site**	**Demand Priority**
Ruiru	Ruiru	1
	Nairobi	2
	Coffee Ruiru	3
Thiririka	Gatundu B	1
	Flower Thiririka	2
	Coffee Thiririka	3
	Premier Bag	4
Ndarugu	Gatundu	1
	Jomo Kenyatta Uinversity	2
	Juja	3
	Flower Ndarugu	4
	Coffee Ndarugu	5

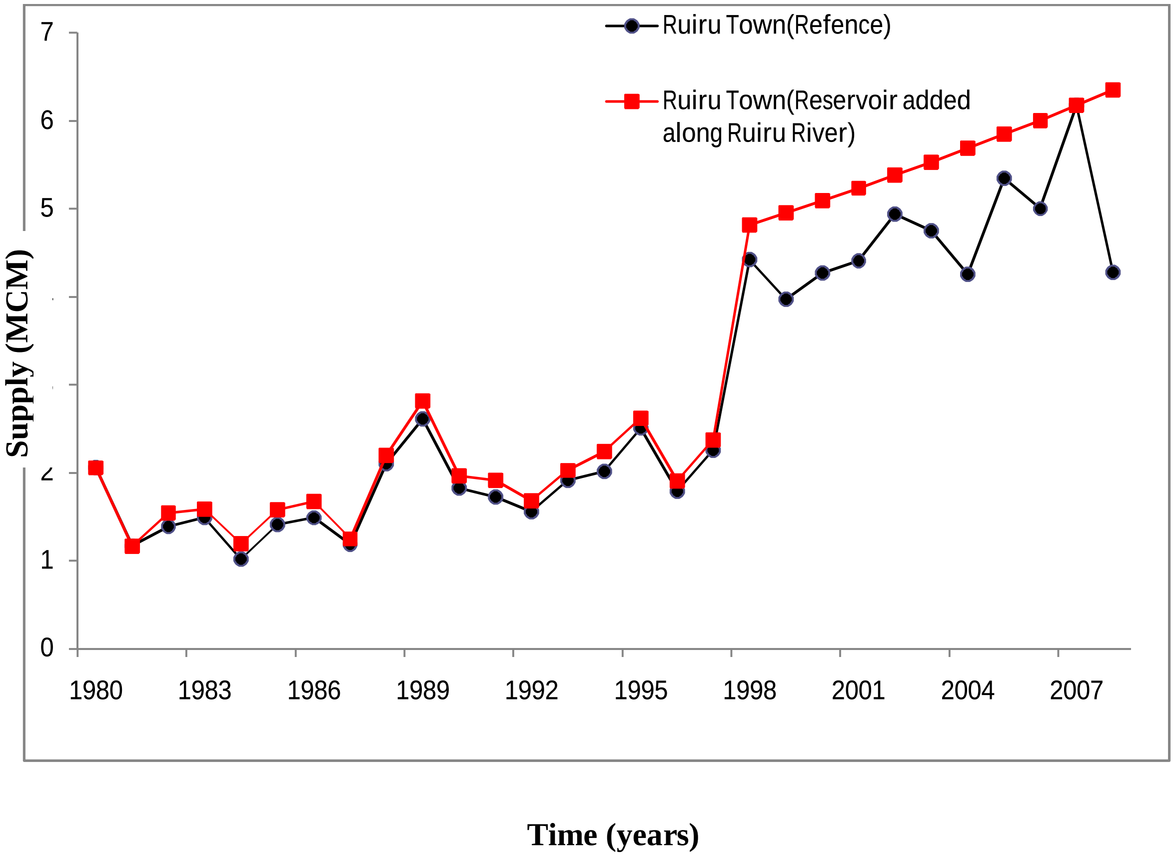
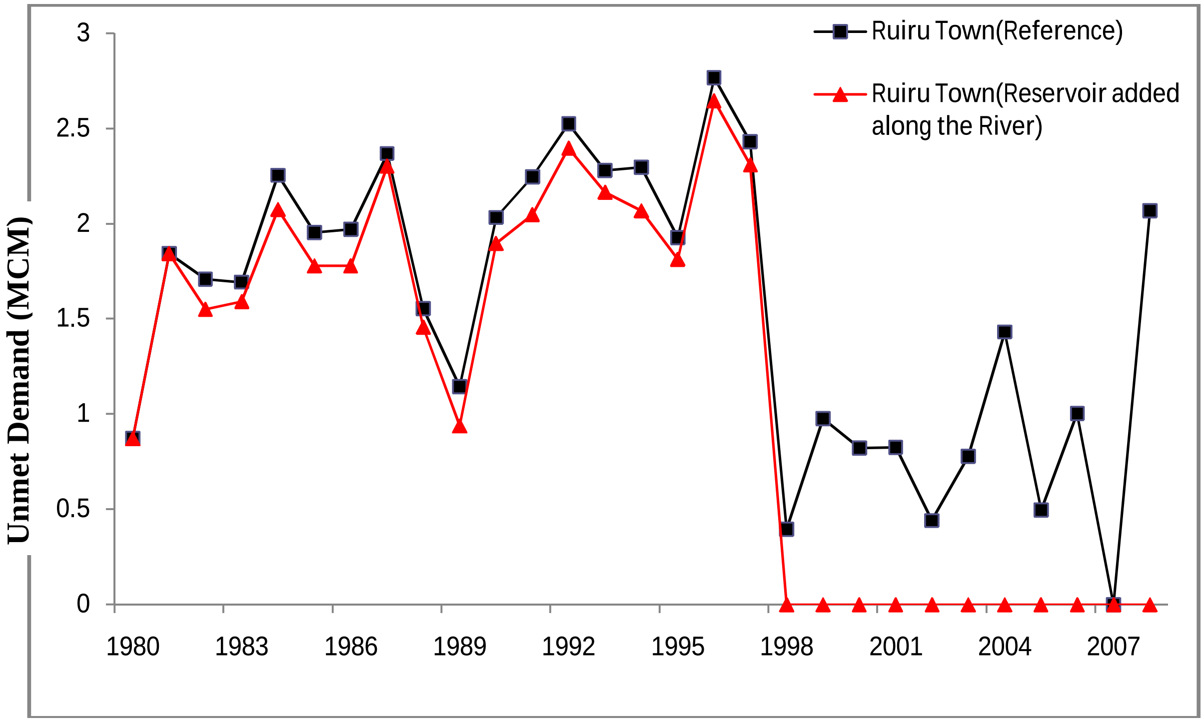
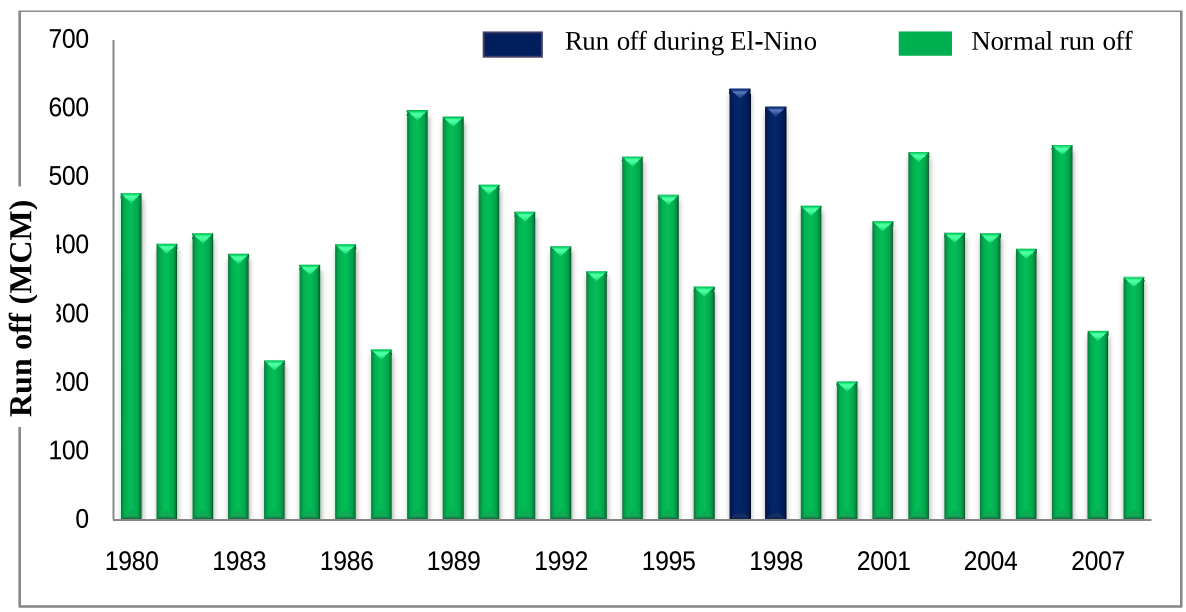


Figure 4.21 Supply delivered for Scenario 4



Time (years)

Figure 4.22 Unmet Demand for Scenario 4



Time (years)

Figure 4.23 Runoff from precipitation for Ruiru catchment

4.3.5 Scenario 5: Environmental Flow Requirement Scenario

Environmental flow is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. The environmental flow requirement along Ndarugu, Thiririka and Ruiru Rivers were set at 21, 10 and 22 m^3/s respectively. For Coffee Ndarugu, the water supply was greatly reduced from January to December compared to reference scenario. In June, July and September, the water supply to Coffee Ndarugu was zero. This is because river flows are low during this period and the little flow is left for the environment. In Gatundu and Juja, the water supply to these demand sites was lower than in reference scenario. The supply to Nairobi was drastically reduced as shown in Figure 4.24 hence increasing the unmet demand. In Coffee Ruiru, Flower Ndarugu, Flower Thiririka, Gatundu and Kenyatta, the demand site coverage was 100% from January to December, the same as in reference scenario but reduced considerably for Coffee Thiririka, Gatudu B, Juja, Premier Bag and Ruiru town. The unmet demand was very high from 1998 to 2008 for Nairobi as shown in Figure 4.25. A constant supply of 7.504 MCM of water was delivered to Coffee Ruiru, meeting all its water demand. In Ruiru town, the unmet demand was comparable to reference scenario from 1980 to 1997, but in 1998 to 2008, the unmet demand increased considerably as shown in Figure 4.26. The unmet demand for Premier Bag started rising from 1988 to 2008. The water supply to Coffee Ndarugu, Coffee Thiririka, Ruiru and Gatundu town was also reduced (Table 4.9) hence increasing the unmet water demand. The unmet demand for domestic was 4.4 MCM in 1980 and rose to 26.7 MCM in 2008 (Table A.11.9).

During this scenario, the environmental flow requirement was first met before supplying water to other demand sites.

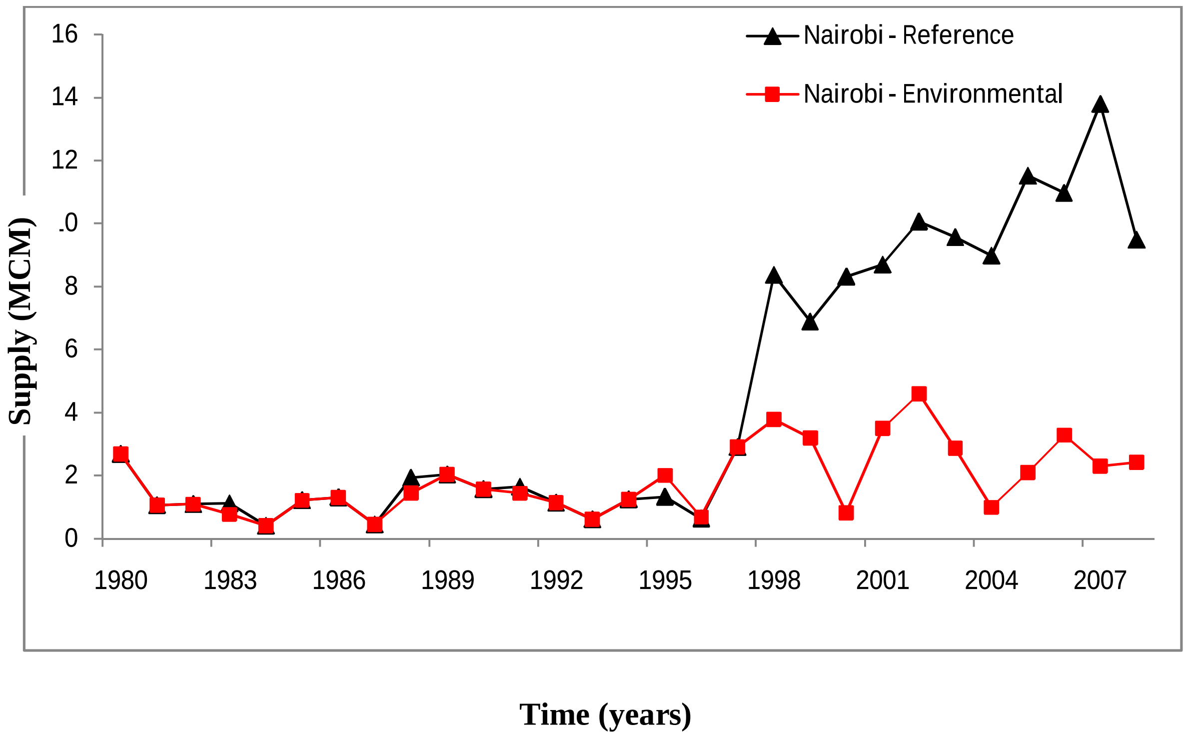


Figure 4.24 Supply Delivered for Scenario 5

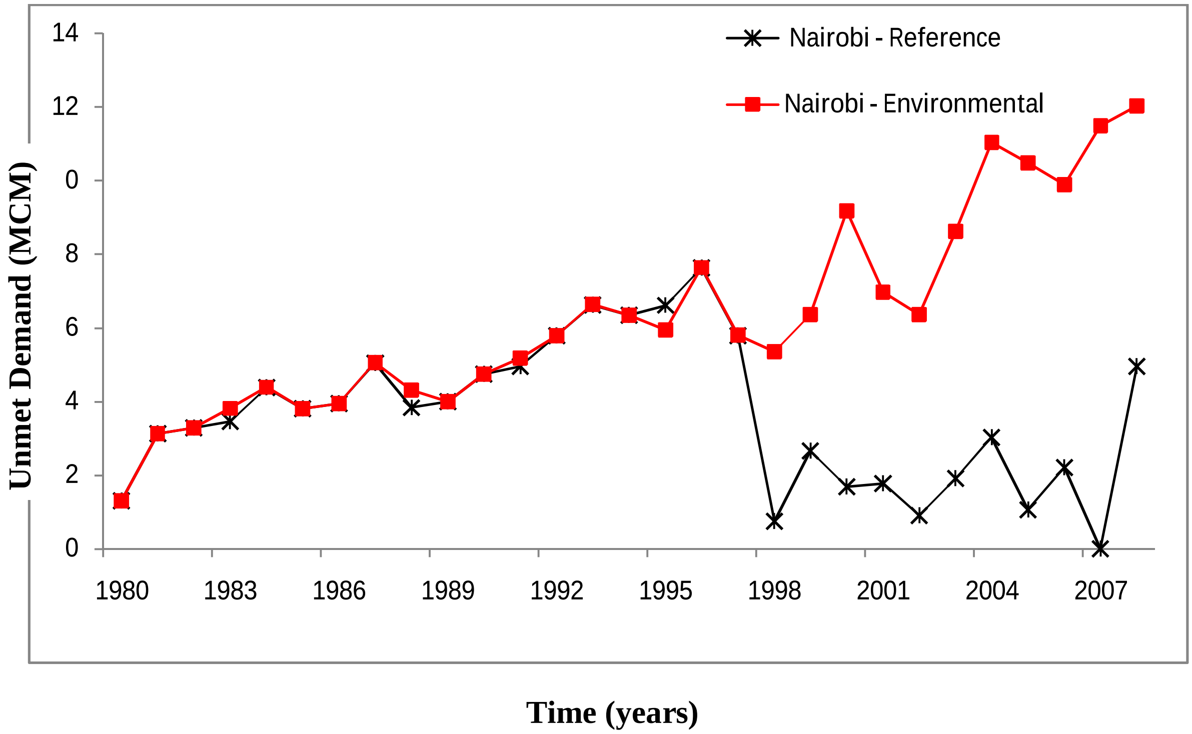


Figure 4.25 Unmet Demand for Scenario 5 for Nairobi City

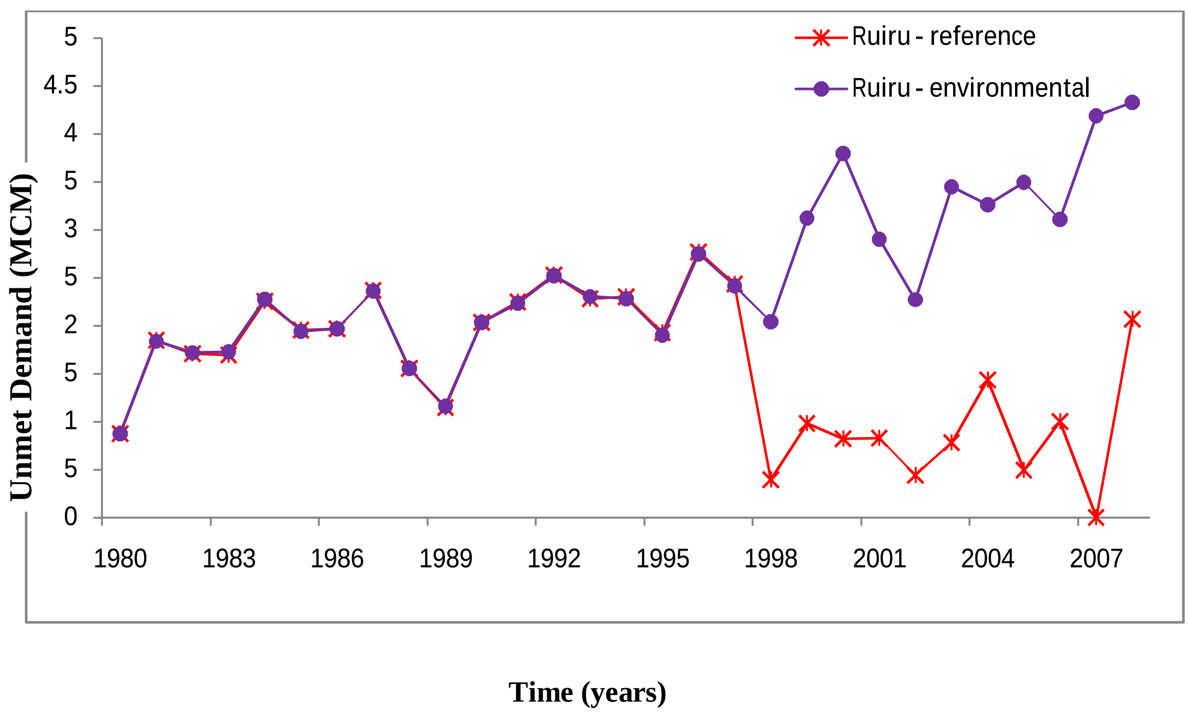


Figure 4.26 Unmet Demand for Scenario 5 for Ruiru Town

Table 4.9 Supply delivered for Scenario 5 in MCM

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Coffee Ruiru	7.504	7.504	7.504	7.504	7.504	7.504	7.504	7.504
Coffee Thiririka	2.643	0.655	1.643	0.977	0.655	0.322	0.977	0.655
Coffee Ndarugu	2.264	0	0.276	0.276	0.276	0	0.276	0.561
Ruiru town	2.057	0.996	2.10	1.558	1.809	1.297	2.421	2.02
Gatundu B	2.9	2	3.322	2.331	3.072	1.939	4.729	3.645
Gatundu	4.3	4.8	5.3	6.0	6.7	7.4	8.3	9.3

4.3.6 Scenario 6: Irrigation Water Quality Constraint

This scenario was tested with agriculture demand sites since water to domestic demand sites is usually treated and of high quality. The inflow of water quality parameters into agriculture demand sites were inputted into the WEAP model based on City Council of Nairobi's standards for irrigation water (Table A.6.3). The water supply and unmet demand in this scenario was the same as in reference scenario for all the demand sites namely Coffee Thiririka, Coffee Ndarugu, Coffee Ruiru, Flower Ndarugu and Flower Thiririka, (Figure 4.27, Table A.11.10 and Table A.11.11). All the water demand for Coffee Ruiru, Flower Ndarugu and Flower Thiririka were all met. The unmet demand for Coffee Thiririka and Coffee Ndarugu is the same as in reference scenario (Figure 4.28). The WEAP model allocated sufficient amount of water to agriculture demand sites to meet their water demand. This implies that the water quality for the three rivers is good for irrigation as the water flow is not constrained by the irrigation water quality requirement (Table 4.10). The water supply to the agriculture demand sites was required to meet water quality specification based on City Council of Nairobi's standard for irrigation water. However, the Total Dissolved Solids for the three rivers was very low ranging from 42.5mg/l to 53.6mg/l against the permissible level of 1200mg/l. The copper levels in the three rivers was nil against a permissible level of 0.05mg/l. Since the irrigation water quality inflow constraint was higher than the water quality of the three rivers, the WEAP model allowed a continuous water supply into the agriculture demand sites.

Table 4.10 Summary of water quality concentrations

	BOD	**TSS**	**TDS**	**Chloride**	**Copper**
Average concentration along Ruiru River	33	4.6	42.5	3.75	0
Average concentration along Thiririka River	13.3	6.65	53.6	5	0
Average concentration along Ndarugu River	31	22	51	2.2	0

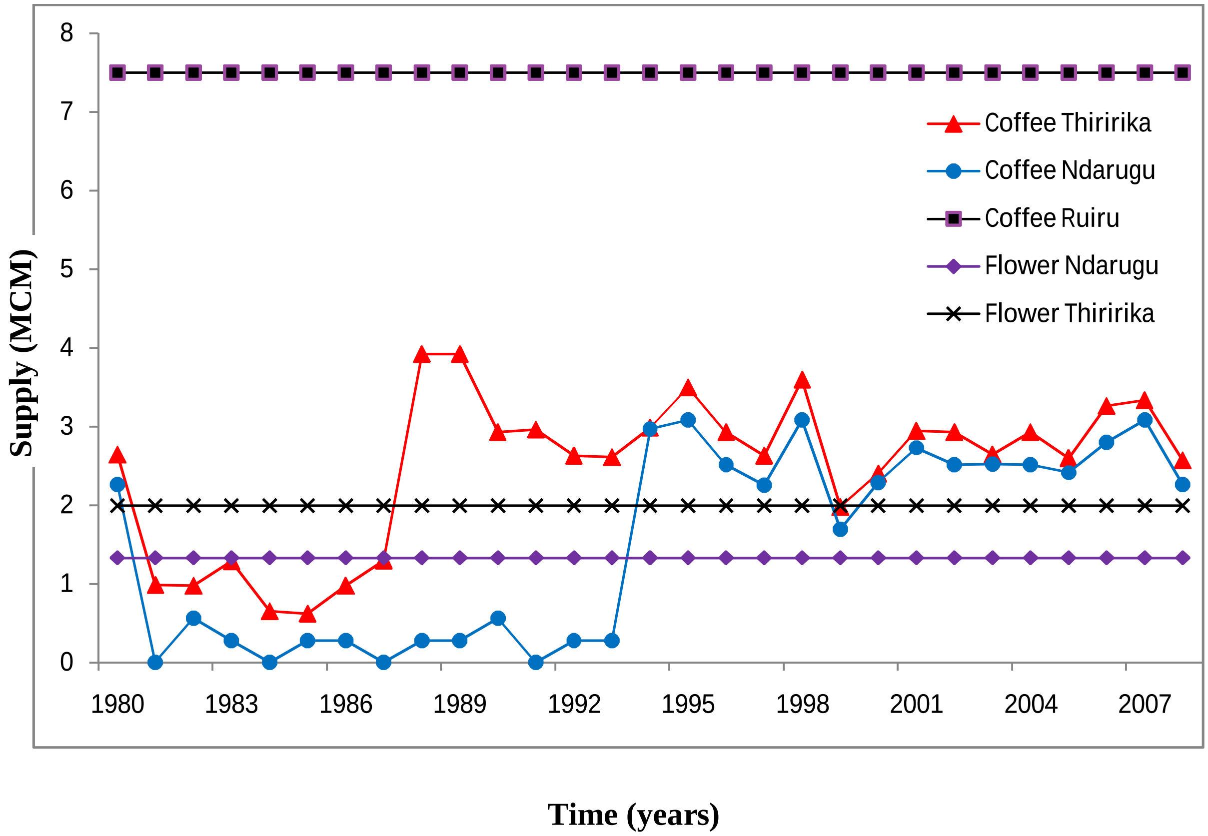


Figure 4.27 Supply delivered for scenario 6

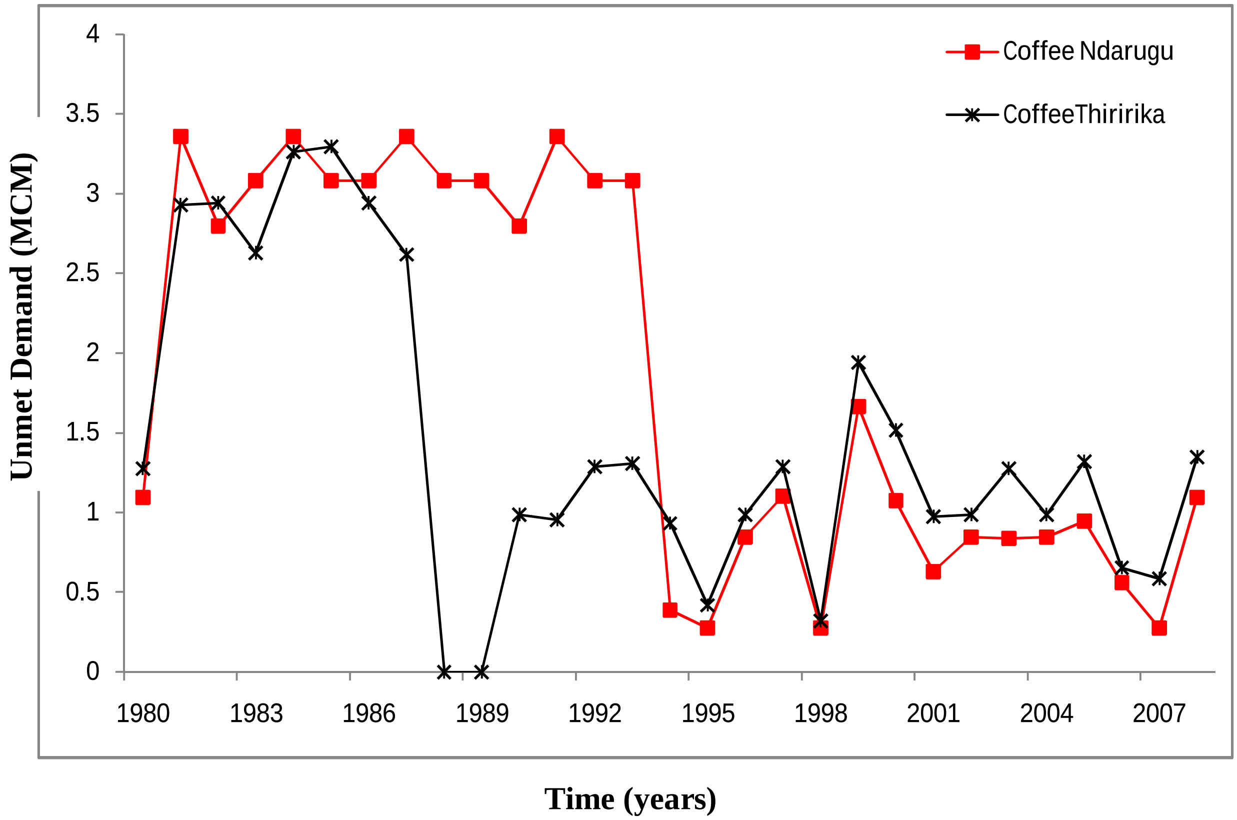


Figure 4.28 Unmet Demand for Scenario 6

4.3.7 Proposed Water Use Management Strategies

The WEAP model evaluated the impacts of different water management strategies under different future scenarios. WEAP model was able to quantify many of the strategies to increase water supply that had been identified. The water plan strategies that were identified and tested through the WEAP model are presented and described in Table 4.11.

Table 4.11: Summary of water plan strategies

No	Strategy	Description
1	Urban water use efficiency	The annual water use rates were adjusted from 90 m^3 to 45 m^3 through efficient water use.
2	Surface storage	The schematic was modified to include water storage facilities (reservoirs) to increase water supply.
3	Conjunctive management and groundwater storage	The supply preferences were adjusted to reflect a shift to relying on groundwater.
4	Land use planning and management	Land use is an input into the WEAP model, which influences rainfall – runoff and consumptive water usage. The forest cover was increased from 10% to 20% to reflect a new management strategy (afforestation).

Table 4.12 Water Management Strategies as implemented in the WEAP model

Water Plan Strategies/Scenarios	Unmet Water Demand (MCM)											
	Nairobi			Ruiru			Gatundu B			Juja		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Urban Water Use Efficiency	0	0.4	3.3	0.02	0	0	0	1.98	2.38	0	0.27	0.36
Conjunctive management and groundwater storage	0.7	1.5	10.5	0	0.3	1.5	0	2	2.58	0	1.25	1.59
Surface storage	0	0	0	0	0	0	0	0	0	0	0	0
Land Use Planning and Management	0.4	1.3	10.3	0	0	0.6	0.2	2.6	3.4	0	1.3	1.6
	Met Water Demand(MCM)											
	Nairobi			**Ruiru**			**Gatundu B**			**Juja**		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Urban Water Use Efficiency	12.3	15	16.1	4.3	5	5.7	10.6	10.2	11.6	3.9	4.2	4.78
Conjunctive management and groundwater storage	24.1	29.8	28.6	8.8	9.9	10.2	12.9	12.8	14.4	8	7.9	8.9
Surface storage	24.1	29.8	29.9	8.9	10.2	11.7	12.9	12.2	13.9	8	7.9	8.9
Land Use Planning and Management	24.4	30.1	29.2	8.8	10.2	11.1	12.7	12.2	13.6	8	7.9	8.9

For the urban water use efficiency strategy and scenario, the annual water use rate was reduced from 90 m^3 (as recommended by Ministry of Water for urban areas) to 45 m^3. By using 45 m^3 as the annual water use rate, the unmet demand for Ruiru was zero for the year 2025. The unmet demand for Nairobi, Gatundu B and Juja was zero for the year 2020. This means the urban water use efficiency is one of the strategies that can be adopted to reduce the unmet demand in the basin. Two reservoirs with combined capacity of 38 MCM were tested with WEAP model along Ruiru and Ndarugu Rivers. The unmet demand for Nairobi, Ruiru, Gatundu B and Juja was zero for the entire period up to 2030. Hence, construction of dams is one of the effective measures that can be undertaken to meet all the water demand in the basin. A groundwater source was inputted into the WEAP schematic to increase water supply in the basin. An available groundwater of 464m^3/day was inputted as the storage capacity. The unmet demand was zero for Ruiru, Gatundu B and Juja for the year 2020. There was a slight increase in unmet demand in the year 2025 and 2030 but the unmet demand was still lower than in reference scenario. Use of groundwater as an alternative source of water is one of the strategies that can be used to reduce the unmet demand. Land use is an input into the WEAP model and it influences rainfall – runoff and consumptive water use. In this strategy, the land was classified for the use of rain fed agriculture, irrigated agriculture, grassland and forestry. The forestry cover was doubled from 10% to 20 %. The unmet demand for Ruiru was zero for the year 2020 and 2025. The unmet demand for Juja was zero for the year 2020. In the other years, the unmet demand was low compared to the reference scenario. This means there was an increased runoff in the basin. Hence, increasing forestry cover as shown in this simulation can increase the runoff and hence reduce the unmet demand. Other outputs for the WEAP model simulations have been summarized in Table 4.12. By combining the four strategies that have been identified, it is evident from Table 4.12 that all the water demand shall be met.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of the research was to verify and calibrate a modeling tool that can be used for sustainable water use planning in Ruiru, Thiririka and Ndarugu Sub-Basins. From this research, the following can be concluded:

1. The water for the three rivers is of good quality for irrigation as evidenced by their low electrical conductivity of below 250µS/cm.

2. From the study, the high value of correlation coefficient (R^2 of 0.849 and 0.88) between simulated and observed flow for model calibration and validation respectively at 3BD05 gauging station implies an acceptable performance of the WEAP model in stream flow generation in Ruiru, Thiririka and Ndarugu sub-basins. The model could therefore be used to predict water demand and supply for future scenarios for Ruiru, Thirirka and Ndarugu sub-basins.

3. The projections of the water demand by the WEAP model in Ruiru, Thiririka and Ndarugu Sub-Basin indicates that it will grow from 75.1 MCM in 2010 to 96.3 MCM and 129.2 MCM in 2020 and 2030 respectively. The unmet demand was 0 MCM in 2010 and 0.6 MCM and 7.2 MCM in 2020 and 2030 respectively with the surface water storage strategy.

4. The use of the proposed reservoirs of 38MCM in Ruiru and Ndarugu Rivers will satisfy the unmet demand in the basin till 2030.

5. The environmental flow requirement (EFR) for Ndarugu, Thiririka and Ruiru Rivers were calculated by IHA model as 21, 10 and 22m^3/s respectively. Providing environmental flow requirement to the rivers reduces the water supply to demand sites hence increasing the unmet demand at demand sites.

6. Four strategies were identified and tested with the WEAP model to increase water supply in the basin. The strategies are: Urban water use efficiency (involves technological or behavioral improvements in indoor or outdoor residential, commercial, industrial and institutional water use that lowers demand and per capita), conjunctive management and groundwater storage, surface storage and land use planning and management. All these strategies improved the water supply and lowering the unmet demand. However, the surface water storage was the most effective strategy resulting into very low unmet demand.

5.2 Recommendations

1. The proposed reservoirs under the surface water strategy should be constructed to meet the current and future water demand.

2. Increase the forest cover in the basin by planting more trees to improve on the rainfall – runoff and consumptive water usage.

3. A groundwater recharge estimation of the basin should be carried out to ascertain the actual storage capacity of the aquifer as it provides an alternative water source.

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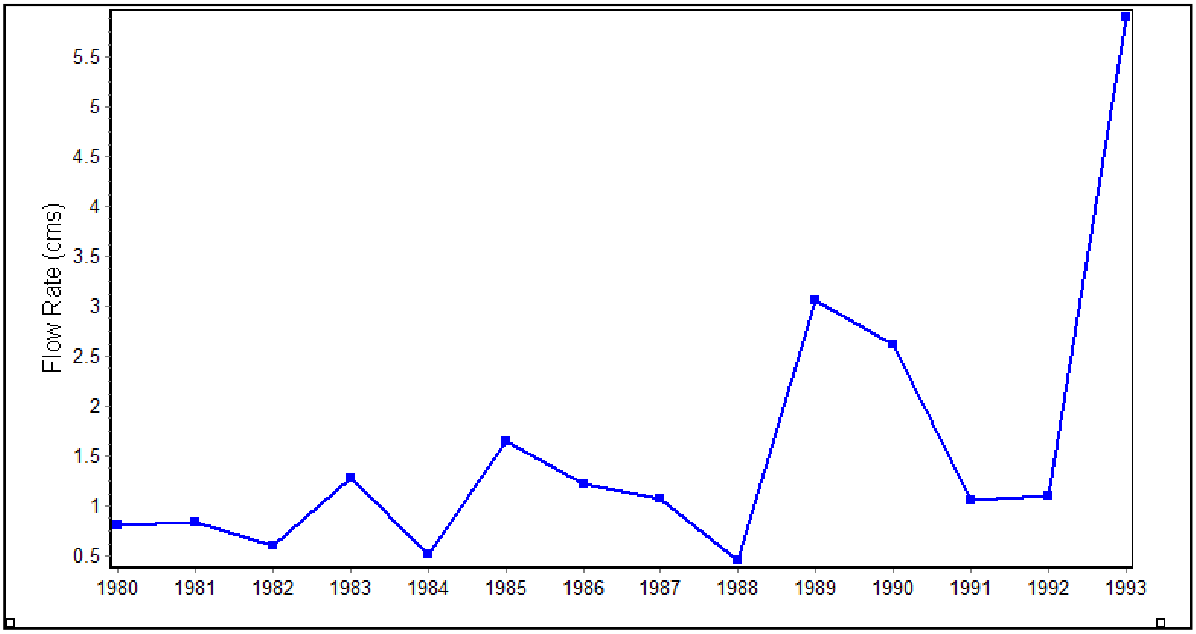
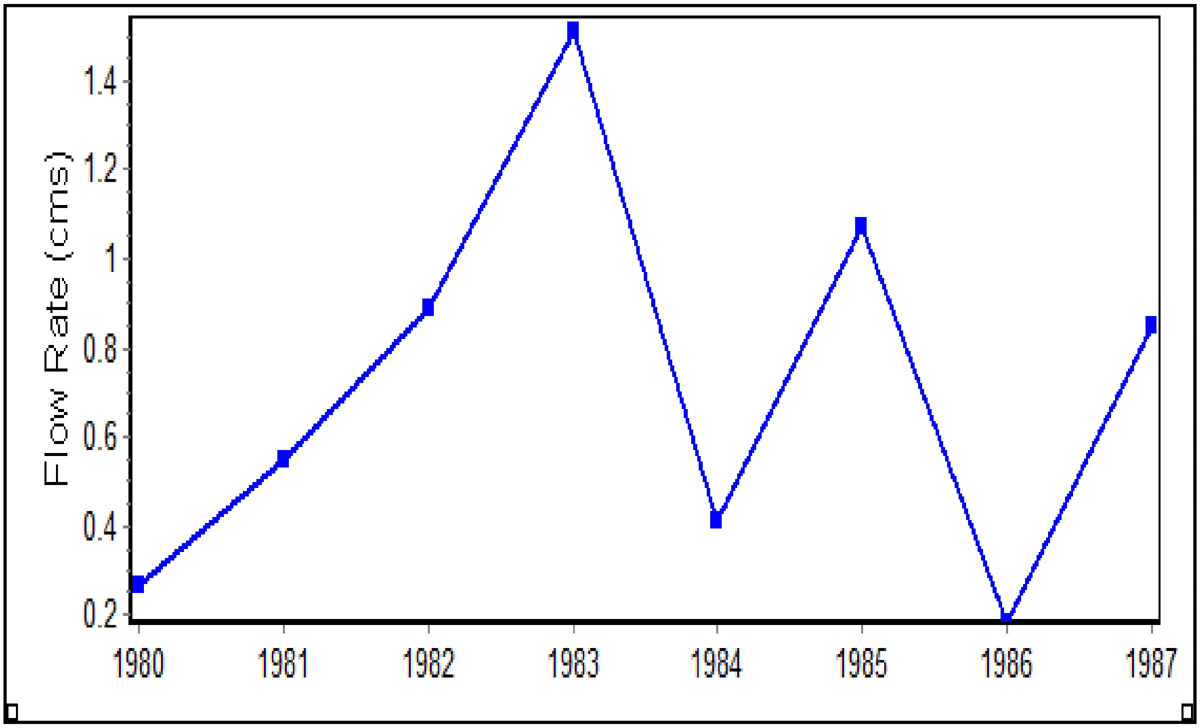
APPENDICES

APPENDIX I Monthly Flows for February



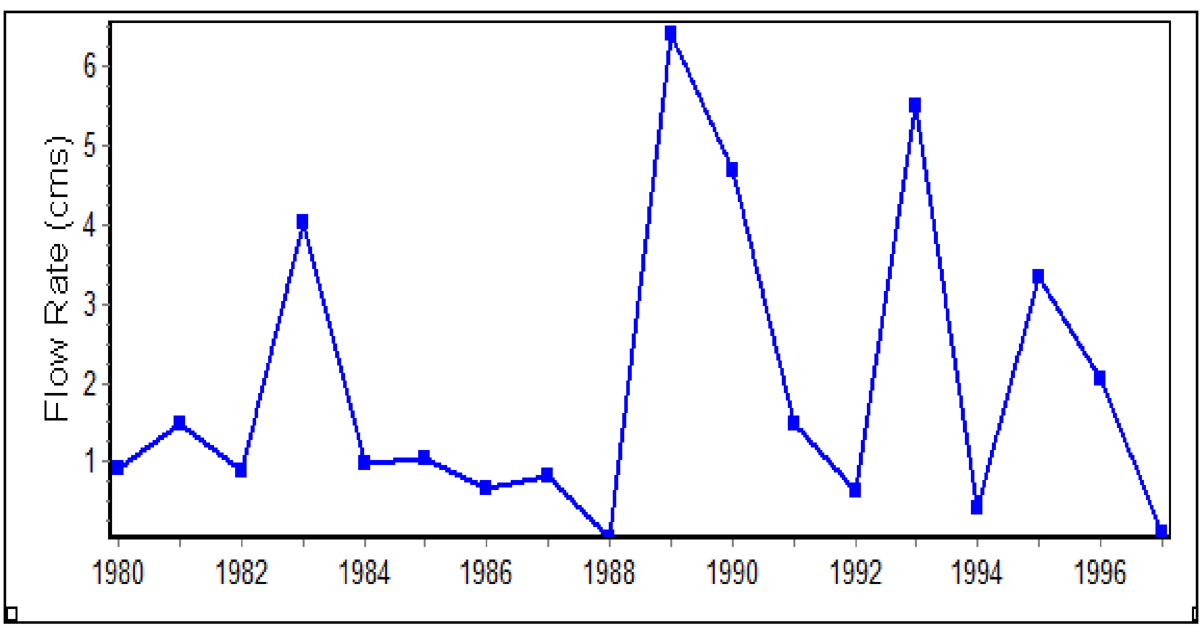
Time (years)

Figure A.1.1 Monthly Flow for February for Ndarugu River



Time (years)

Figure A.1.2 Monthly Flows for February for Thiririka River



Time (years)

Figure A.1.3 Minimum Flows for February for Ruiru River

APPENDIX II Quarrying Activities along Ruiru and Ndarugu Sub-Basins

Figure A.2.1 Quarrying activities along Ndarugu River

Figure A.2.2 Quarrying activities within the riparian reserve along Ruiru River

APPENDIX III Pollution generation along Ruiru and Ndarugu Sub-Basins

Figure A.3.1 Coffee factories effluent along Ndarugu River

APPENDIX IV Daily discharge hydrographs

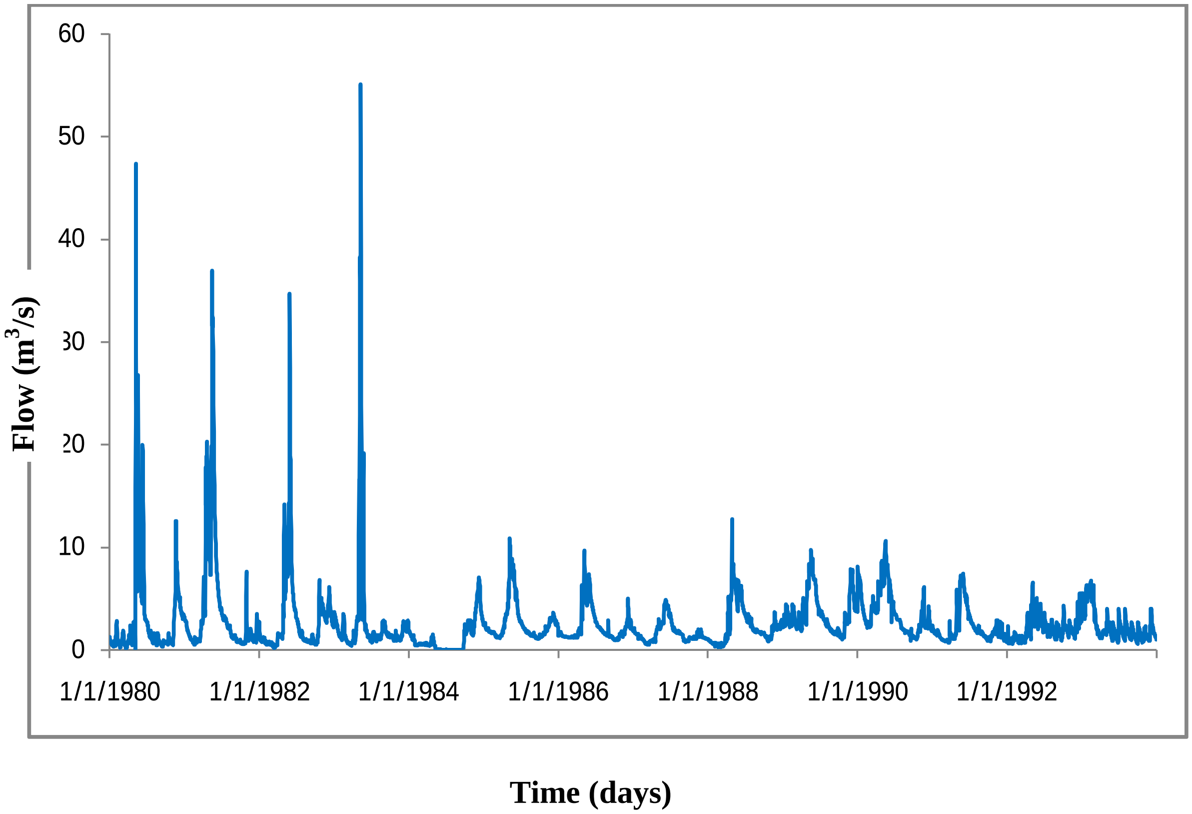


Figure A.4.1 Daily discharge hydrograph for Ndarugu River (3CB05)

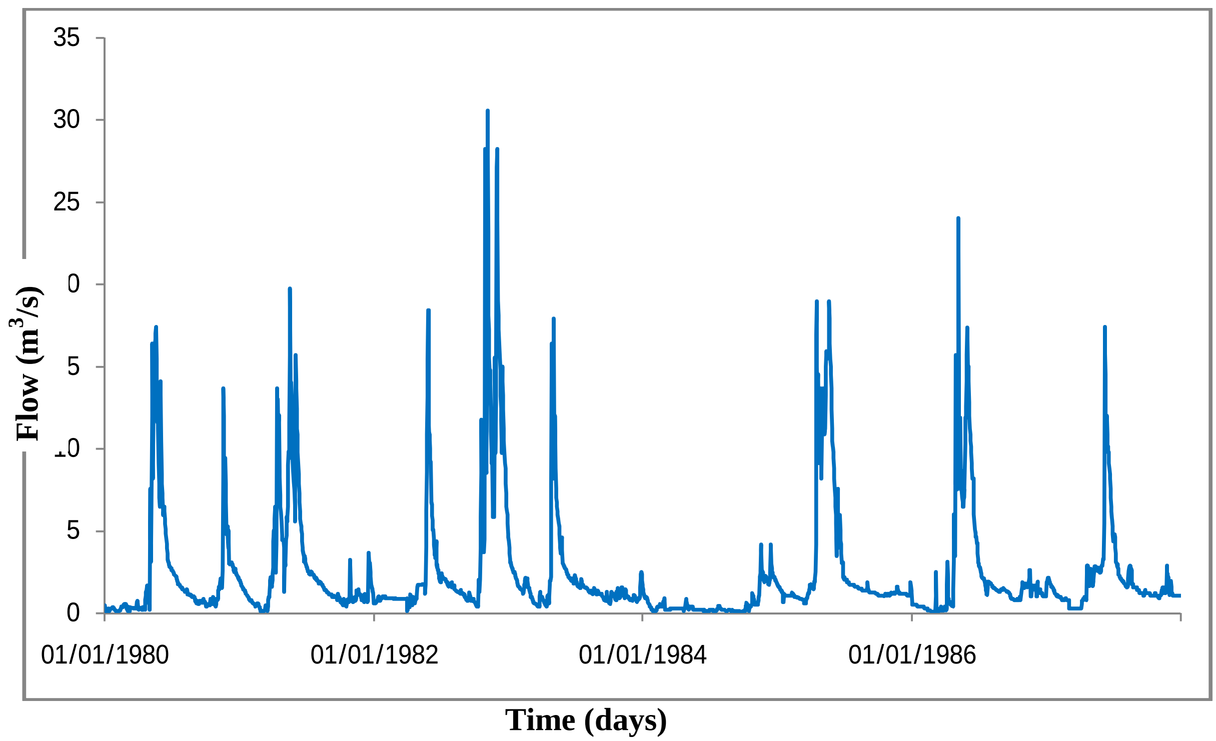


Figure A.4.2 Daily discharge hydrograph for Thiririka River (3BD05)

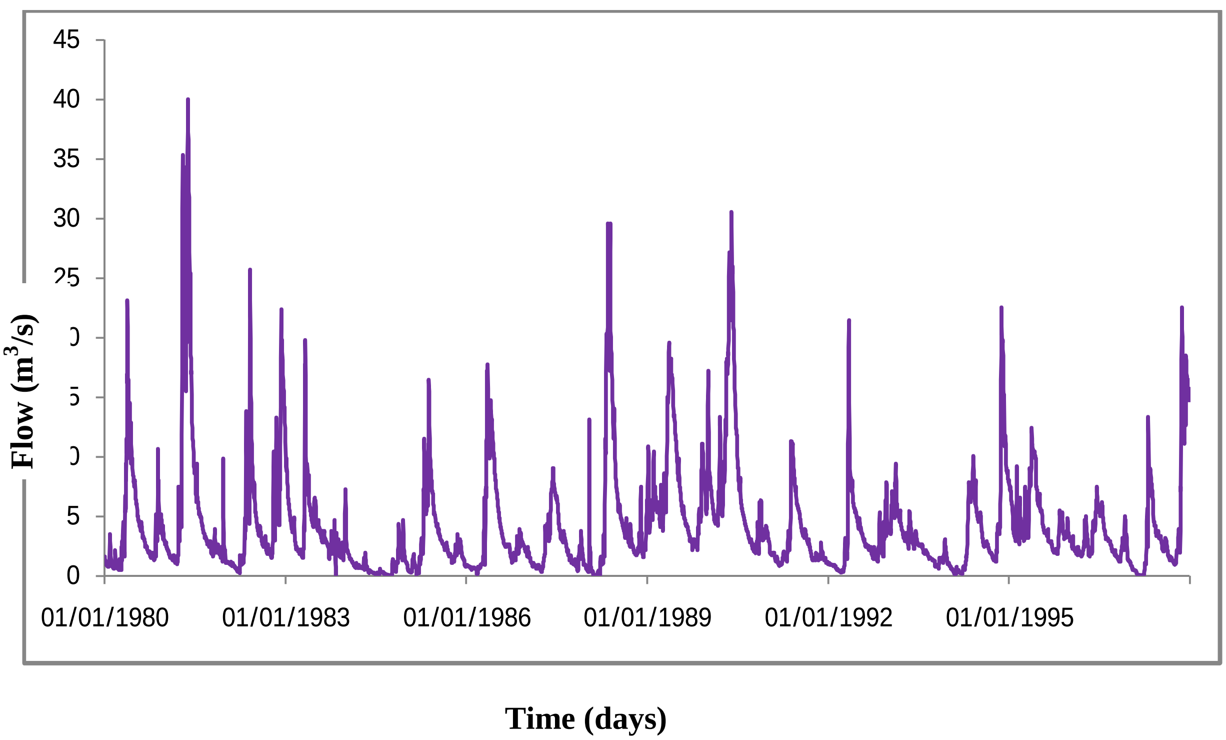


Figure A.4.3 Daily discharge hydrograph for Ruiru River (3BC12)

APPENDIX V Average Monthly Precipitation

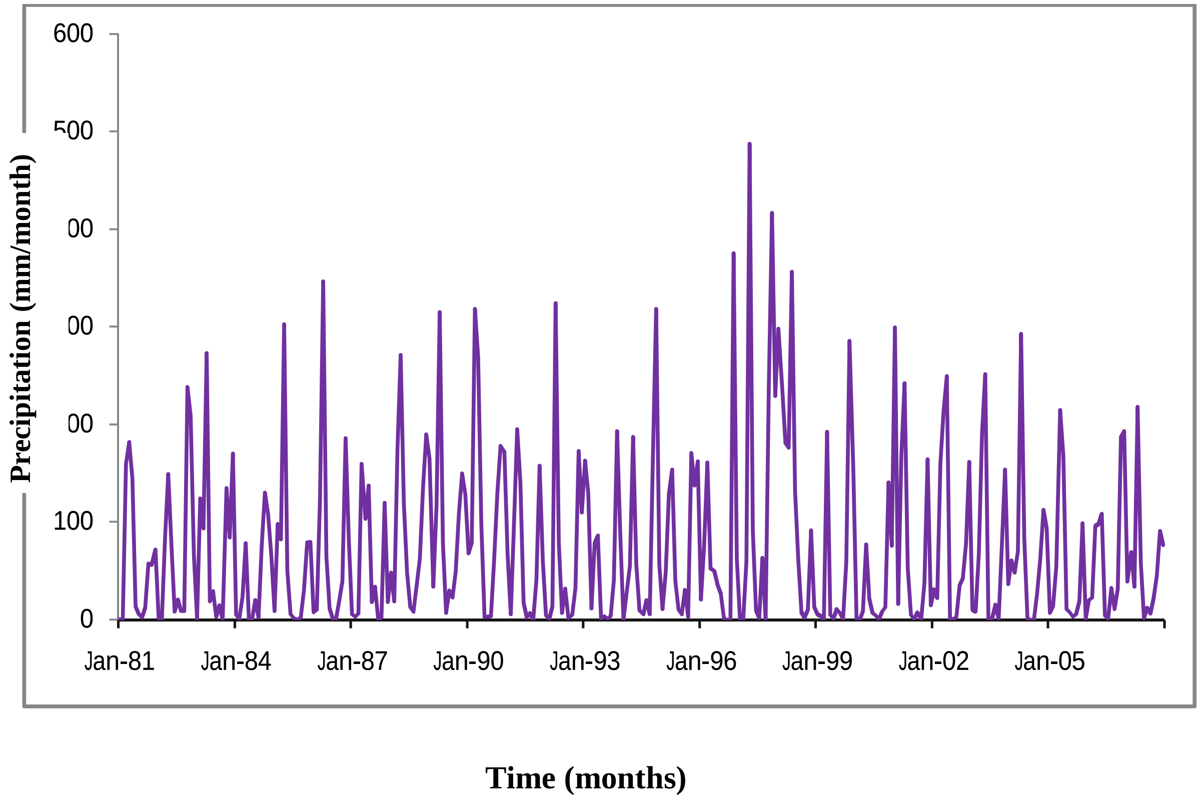


Figure A.5.1 Average Monthly Precipitation for Ndarugu sub-catchment for four stations

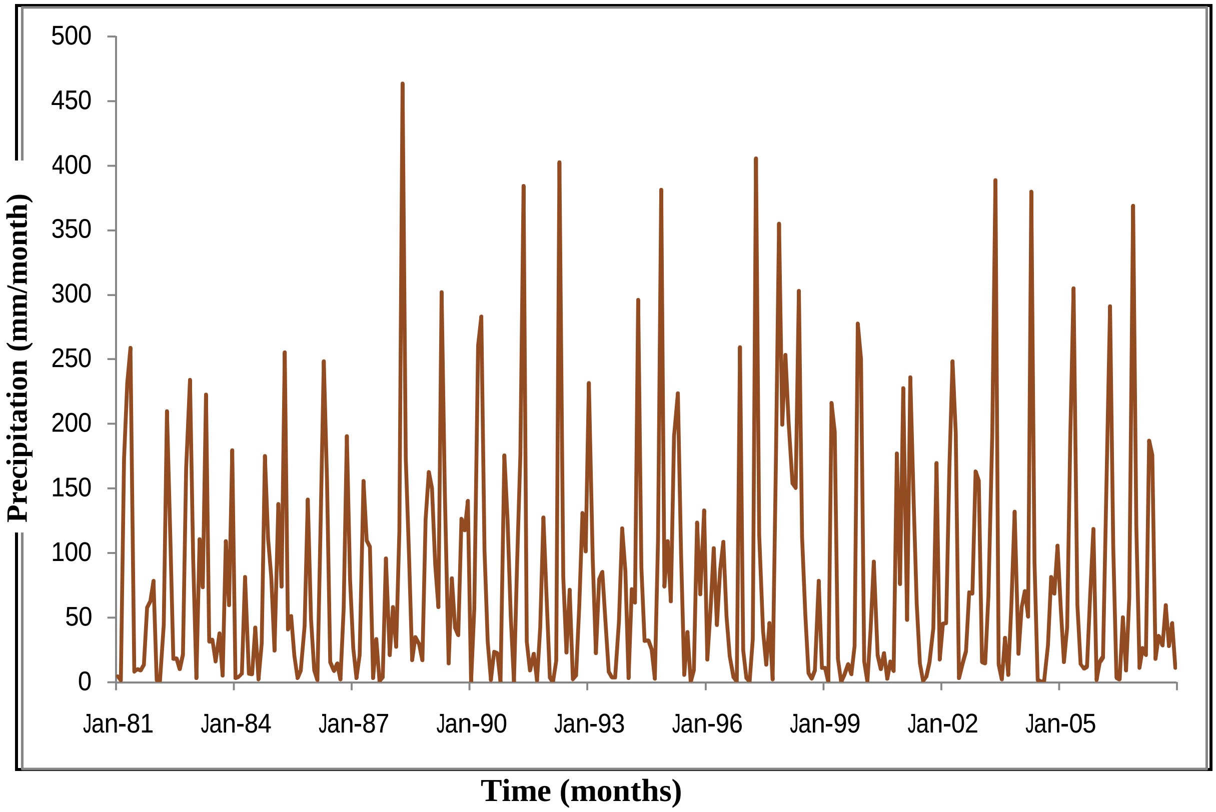


Figure A.5.2 Average Monthly Precipitation for Ruiru sub-catchment for four stations

Table A.5.3 Average Annual Rainfall

Year	**Average Annual Rainfall(mm)**	**Definition**
1980	799	Dry
1981	709	Dry
1982	874	Normal
1983	948	Normal
1984	512	Very Dry
1985	742	Dry
1986	893	Normal
1987	610	Dry
1988	1125	Wet

1989	1208	Very Wet
1990	1384	Very Wet
1991	795	Dry
1992	783	Dry
1993	801	Dry
1994	911	Normal
1995	906	Normal
1996	863	Normal
1997	1598	Very Wet
1998	1567	Very Wet
1999	726	Dry
2000	359	Very Dry
2001	1010	Normal
2002	1000	Normal
2003	814	Dry
2004	852	Wet
2005	606	Dry
2006	808	Dry
2007	675	Dry

APPENDIX VI Water Qualities

Table A.6.1 Water qualities during dry season

Location	River	BOD_5 (mg/l)	TSS (mg/l)	TDS (mg/l)	EC (µs/cm)	Chloride (mg/l)	Turbidity (NTU)	Copper (mg/l)
Kamwangi	Ndarugu	5.3	4.7	58.6	125.6	0.8	0	0
Juja farm	Ndarugu	45.6	53.3	72.0	132.0	4.5	0	0
Ruiru dam	Ruiru	2.0	2.0	14.3	60.2	3.0	4	0
Ruiru bridge	Ruiru	8.3	7.3	75.7	99.1	5.5	6	0
Mukini	Thiririka	8.0	3.0	30.0	67.5	3.5	20	0
Kalimoni primary	Thiririka	17.9	9.3	105.7	173.7	13.0	39	0

Table A.6.2 Water qualities during wet season

Location	River	BOD_5 (mg/l)	TSS (mg/l)	TDS (mg/l)	EC (µs/cm)	Chloride (mg/l)	Turbidity (NTU)	Copper (mg/l)
Kamwangi	Ndarugu	25	3.2	35	58	1.5	244	0
Juja farm	Ndarugu	51	30	42	70	2.0	544	0
Ruiru dam	Ruiru	60	5	33	55	2.0	195	0
Ruiru bridge	Ruiru	62	4.3	47	78	4.5	228	0
Mukini	Thiririka	14	2.3	24	40	0.5	345	0
Kalimoni primary school	Thiririka	406	12	55	92	3.5	670	0

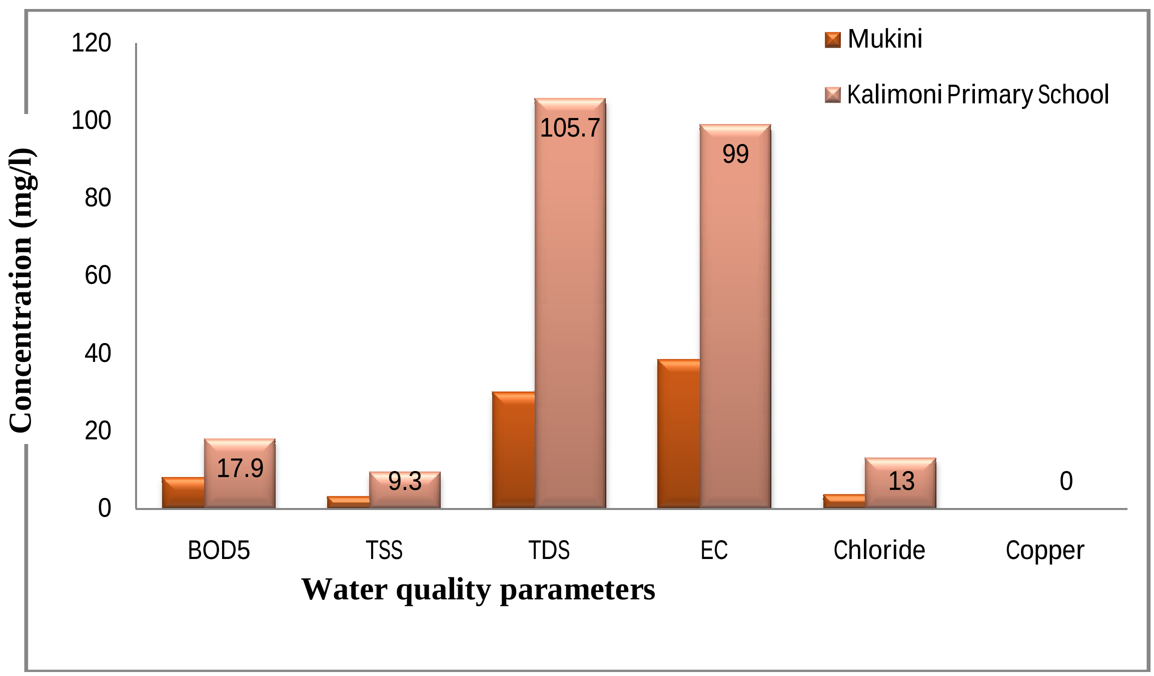


Figure A.6.1 Water quality parameters for Thiririka River during the dry season

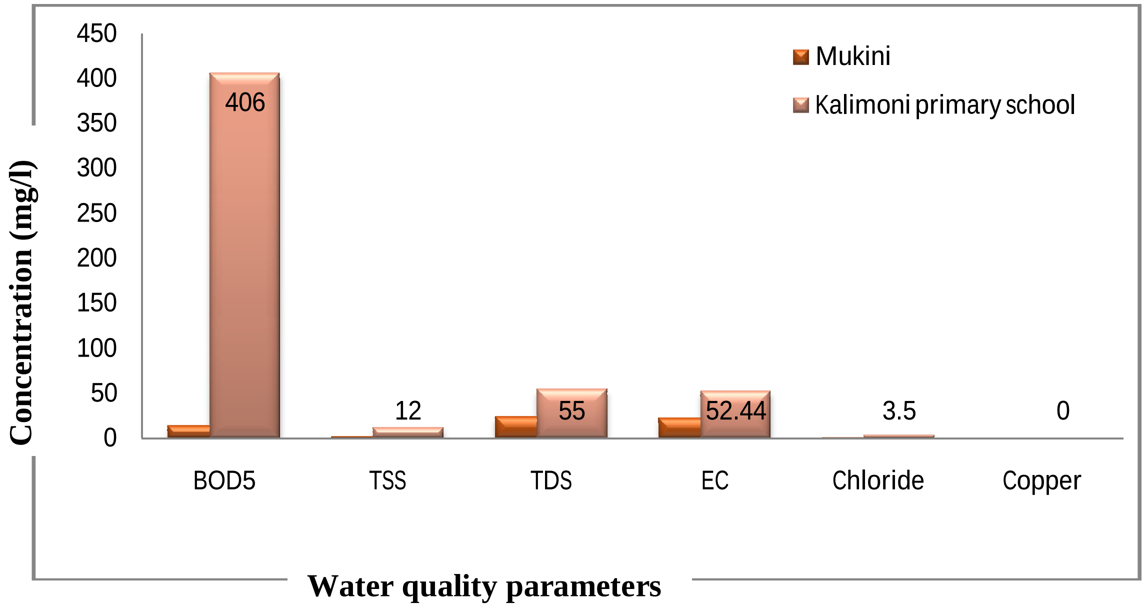


Figure A.6.2 Water quality parameters for Thiririka River during the wet season

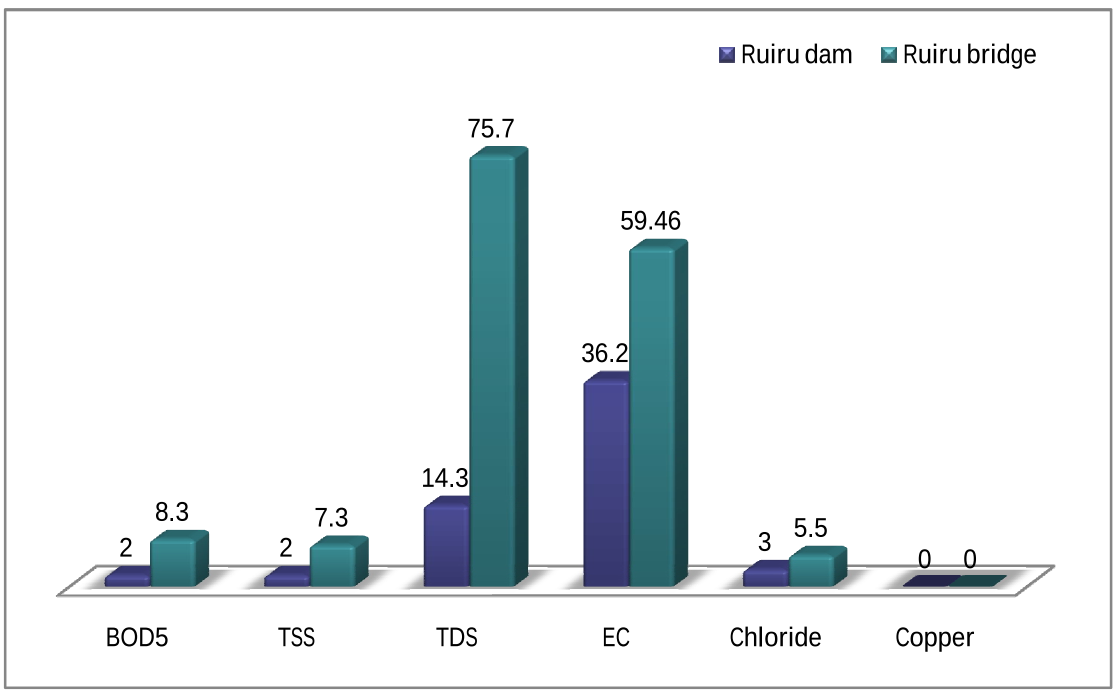


Figure A.6.3 Water quality parameters for Ruiru River during the dry season

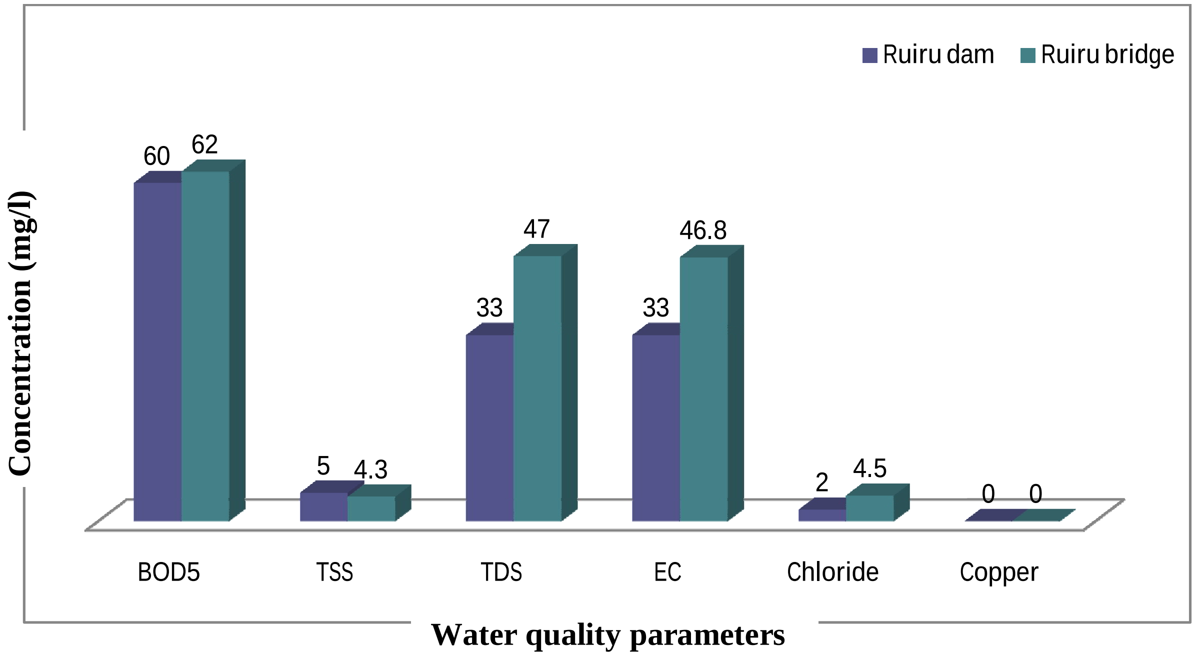


Figure A.6.4 Water qualities parameters for Ruiru River during the wet season

Table A.6.5 Standards for irrigation water

No	**Parameter**	**Permissible Level**
1	pH	6.5 – 8.5
2	Aluminium	5(mg/l)
3	Boron	0.1(mg/l)
4	Chloride	0.01(mg/l)
5	Copper	0.05(mg/l)
6	Iron	1(mg/l)
7	Total dissolved solids	1200(mg/l)

Source: City Council of Nairobi (Environmental Management and Conservation By-Law, 2009)

Table A.6.6 Classification of water quality

Class	Water Quality Index range
Excellent	90 - 100
Good	70 - 90
Fair	50 - 70
Bad	25 - 50
Very Bad	0 - 25

Source: CCME, 2001

Table A.6.7 USDA Salinity Laboratory's classification of saline irrigation water based on salinity level, potential injury to plants

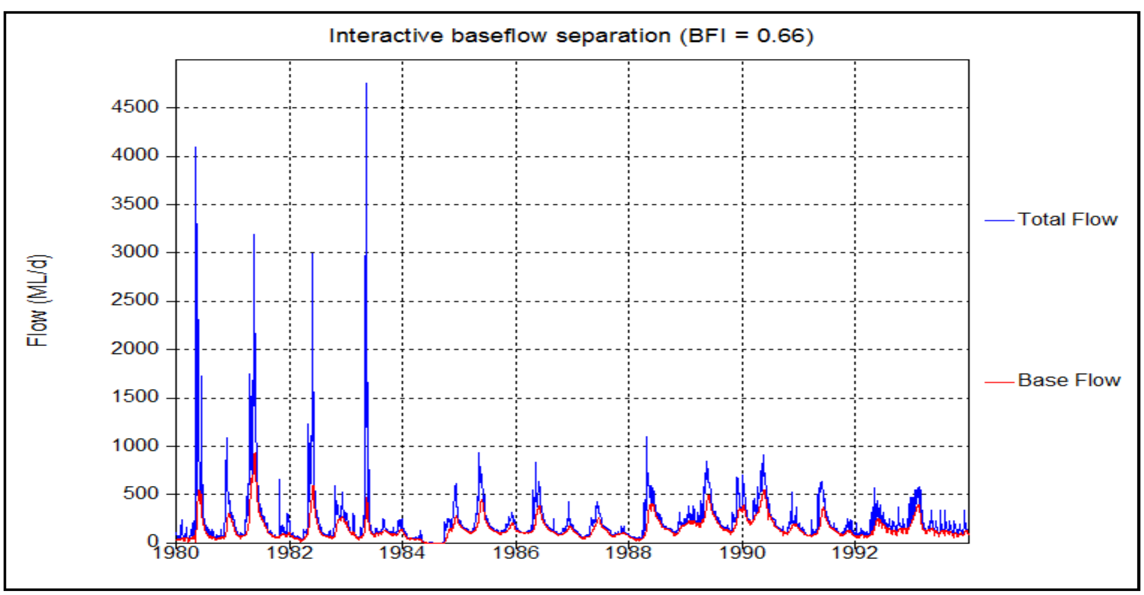
Salinity Class	**Electrical Conductivity(μS/cm)**	**Total dissolved salts(ppm)**	**Potential injury and necessary management for use as irrigation water**
Low	<250	< 150	Low salinity hazard; generally not a problem; additional management not needed
Medium	750-250	500-150	Damage to sensitive plants may occur, Occasional flushing with low salinity water may be necessary
High	2250-750	1500-500	Damage to plants with low tolerance to salinity will likely occur. Plant growth and quality will be improved with excess irrigation for leaching and/or periodic use of low salinity water and good drainage provided

Source: Clemson University, 2001

APPENDIX VII Base flow separation

Table A.7.1 Base flow separation for Thiririka River

Year	Flow(ML/day)	Base flow(ML/day)	Base flow index
1980	76195.46	37792.46	0.50
1981	85161.45	50326.73	0.59
1982	124581.55	65156.88	0.52
1983	60984.49	40594.01	0.66
1984	18581.14	11577.63	0.62
1985	98847.01	61683.75	0.62
1986	80533.0	46775.21	0.58
1987	64233.69	41283.50	0.64

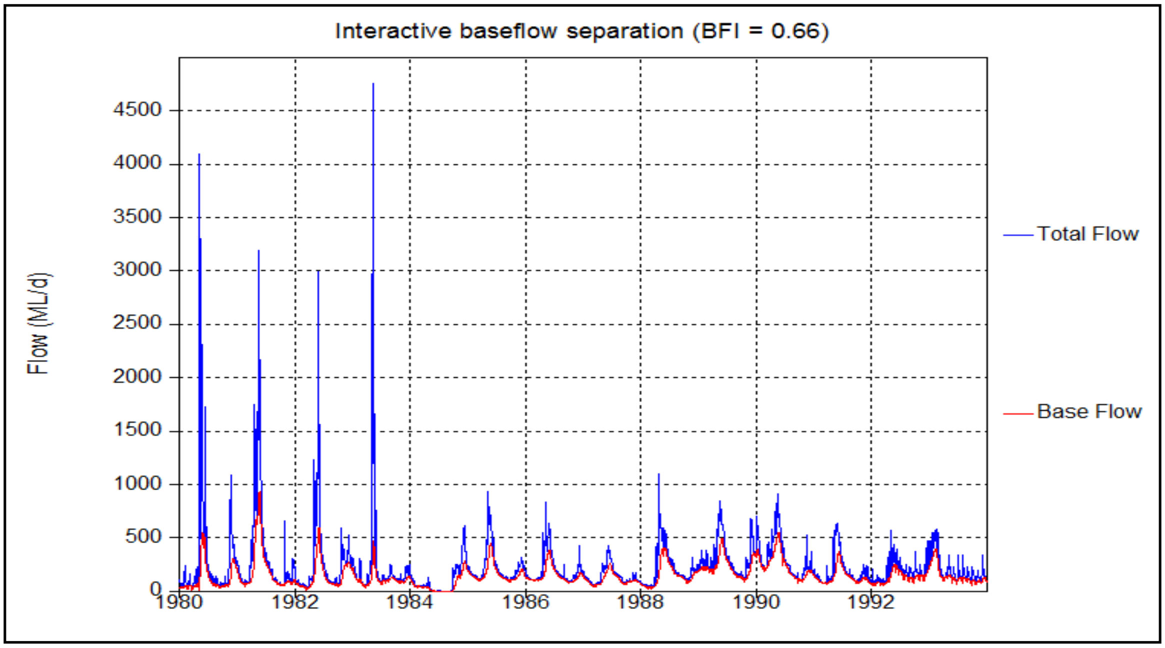


Time (years)

Figure A.7.1 Base flow separation for Thiririka River

Table A.7.2 Base flow separation for Ruiru River

Year	Flow(ML/day)	Base flow(ML/day)
1980	126290.50	82430.40
1981	222803.55	141122.70
1982	158637.91	94209.72
1983	125900.90	94807.08
1984	27139.44	17674.26
1985	94960.13	64591.99
1986	119343.33	81038.53
1987	78367.57	54312.32
1988	163431.06	100586.03
1989	226997.91	168806.58
1990	252621.8	182229.75
1991	91195.02	67431.71
1992	95800.98	65547.25
1993	91448.82	75845.47
1994	136111.48	84618.77
1995	149190.64	117392.73
1996	92527.13	71414.91
1997	143944.69	91734.98



Time (years)

Figure A.7.2 Base flow separation for Ruiru River

APPENDIX VIII Monthly Run off

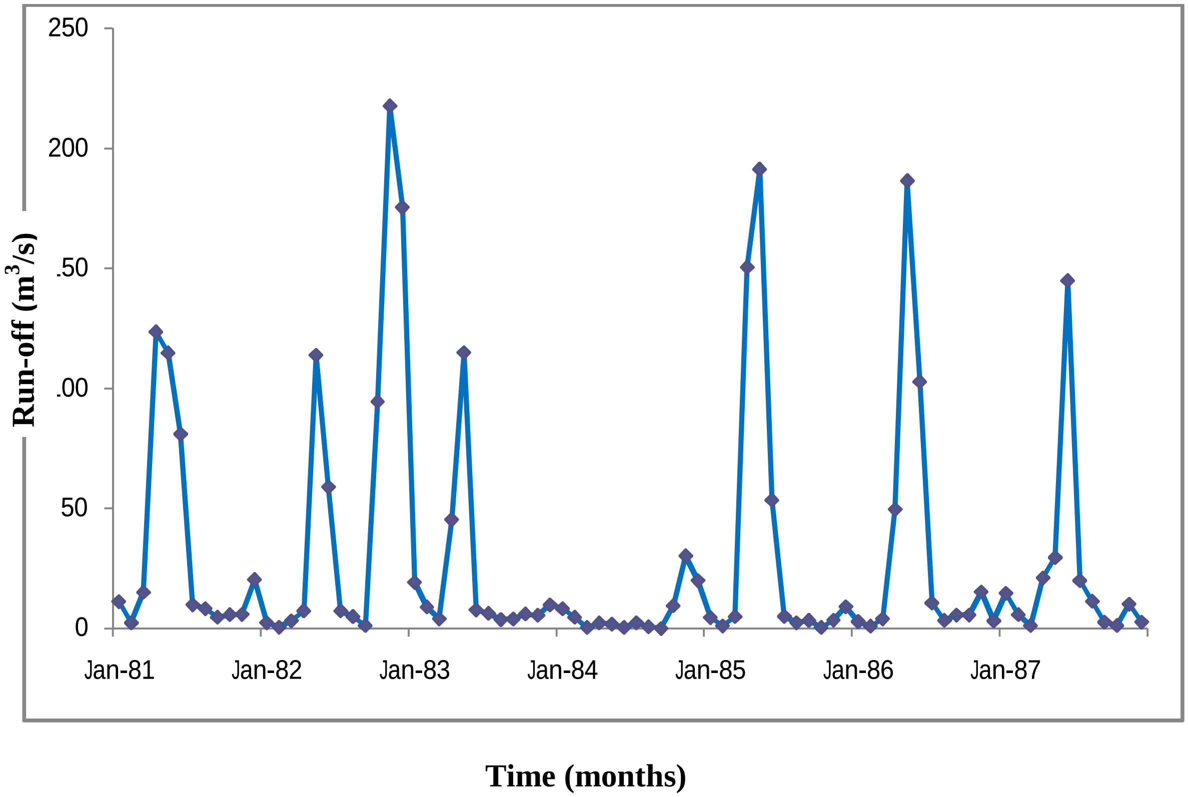


Figure A.8.1 Direct Runoff for Thiririka River (3BD05)

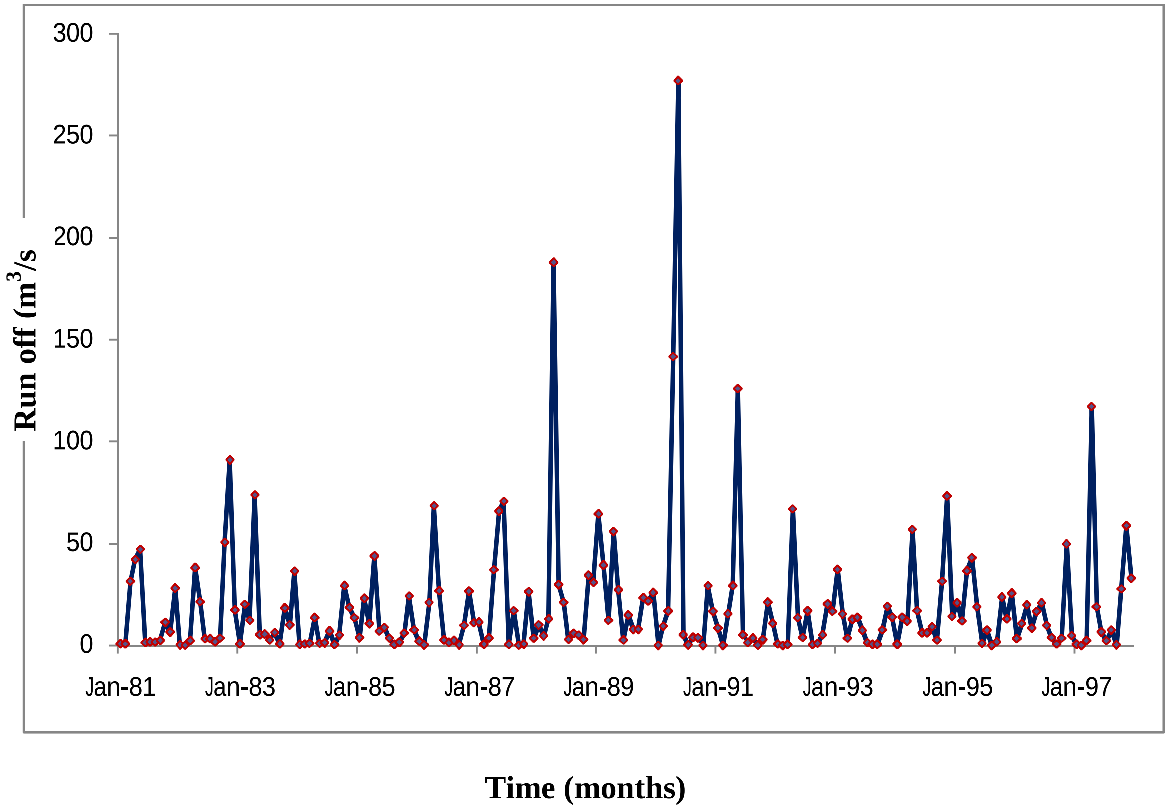
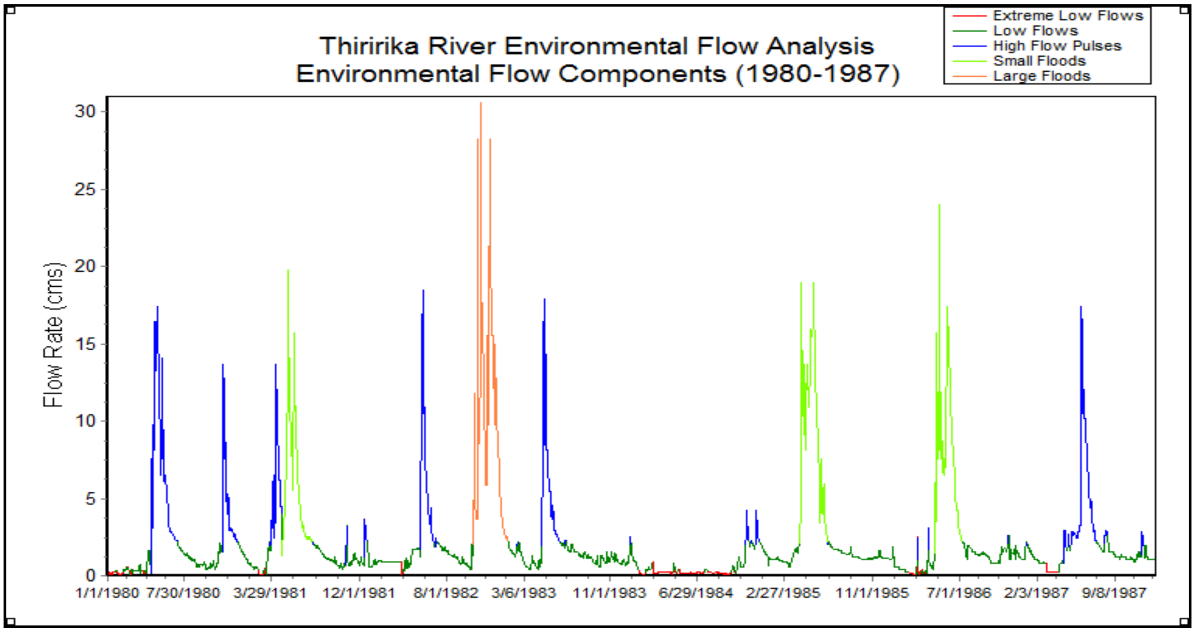


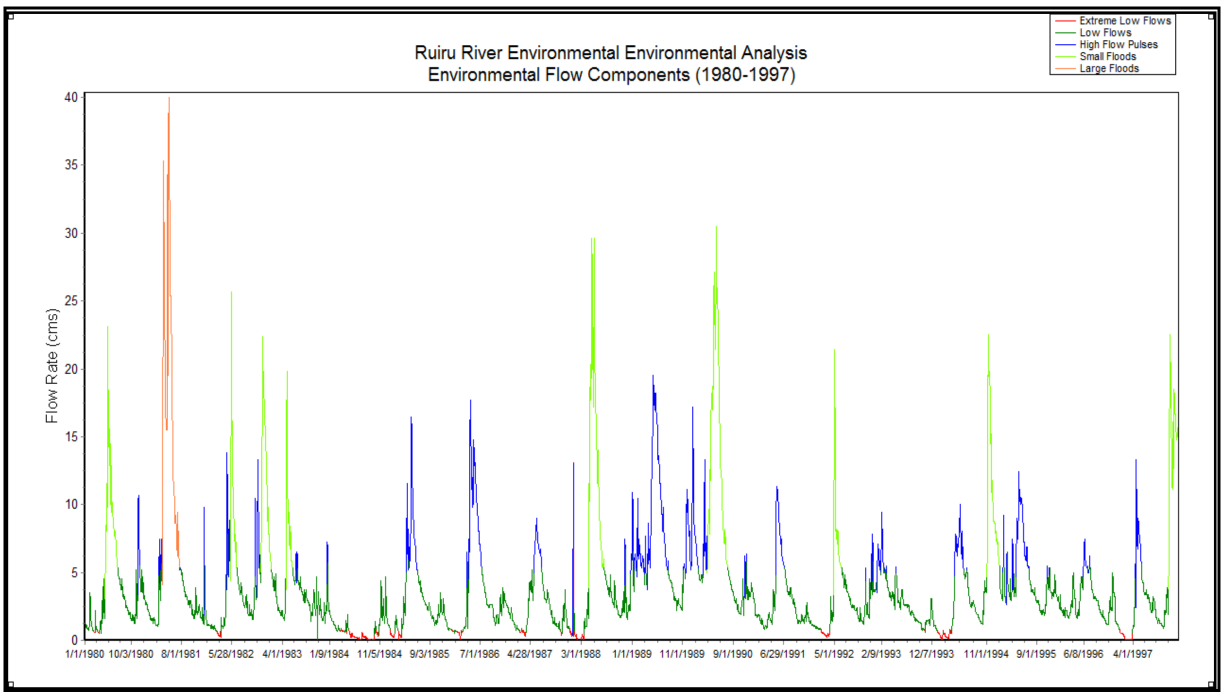
Figure A.8.2 Monthly Runoff for Ruiru River (3BC12)

APPENDIX IX Environmental Flow Components



Time (days)

Figure A.9.1 Environmental Flow Components for Thiririka River



Time (days)

Figure A.9.2 Environmental Flow Components for Ruiru River

APPENDIX X. Observed and Simulated flows

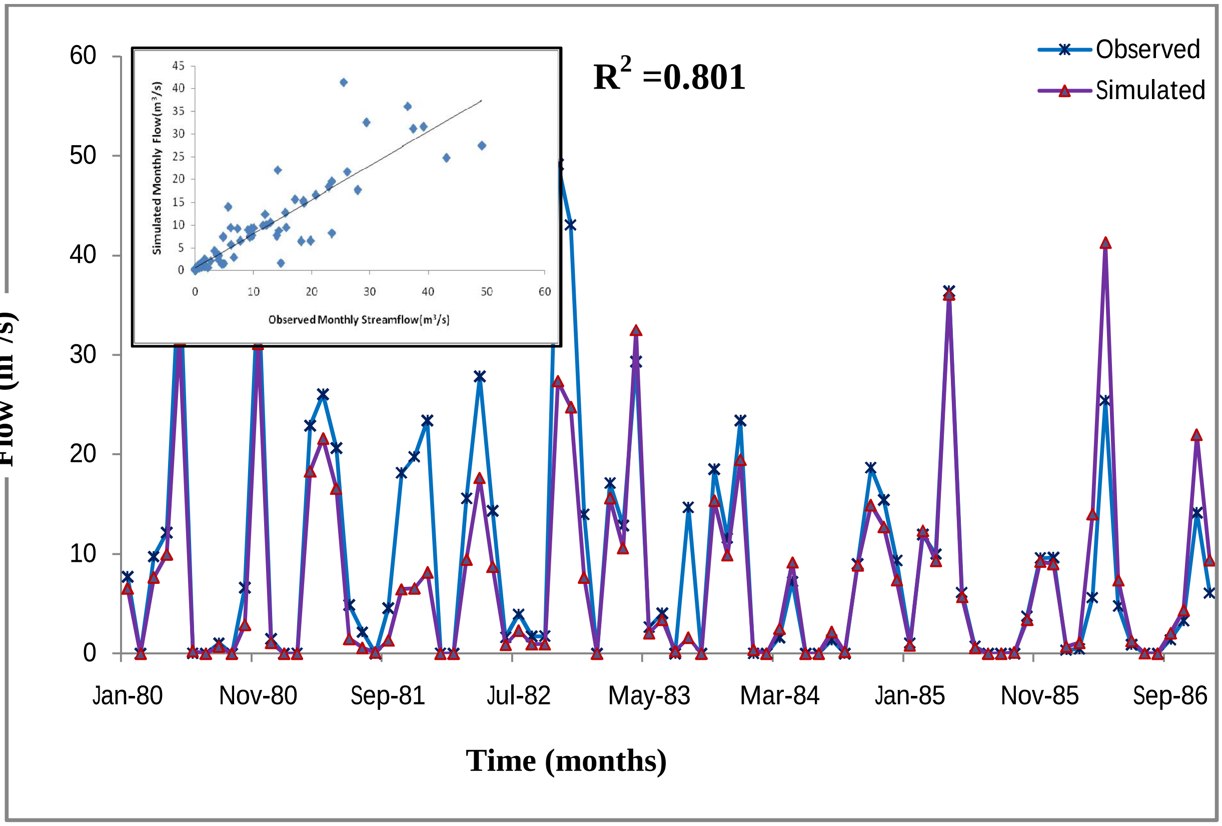


Figure A.10.1 Observed and simulated stream flow for Ndarugu River at station 3CB05 with scatter plot showing the correlations during calibration

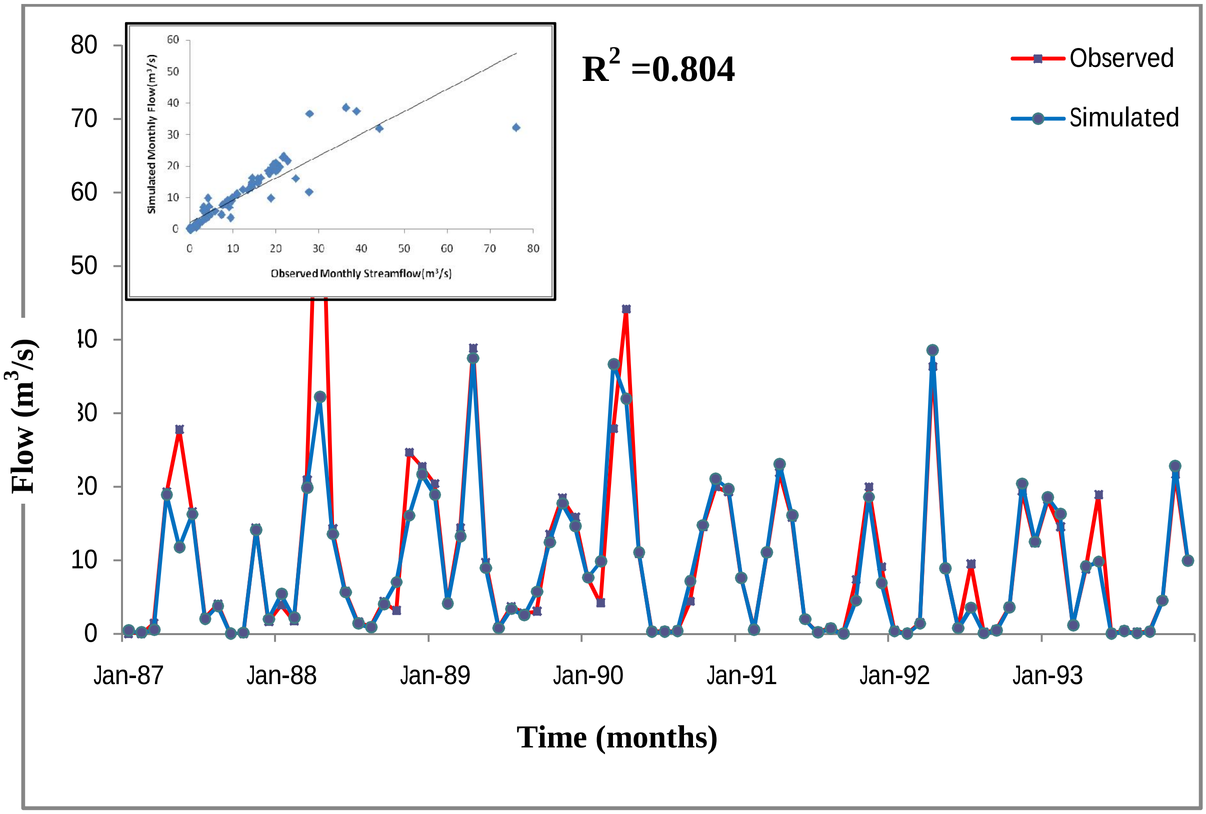


Figure A.10.2 Observed and simulated stream flow for Ndarugu River for station 3CB05 with scatter plot showing the correlations during validation

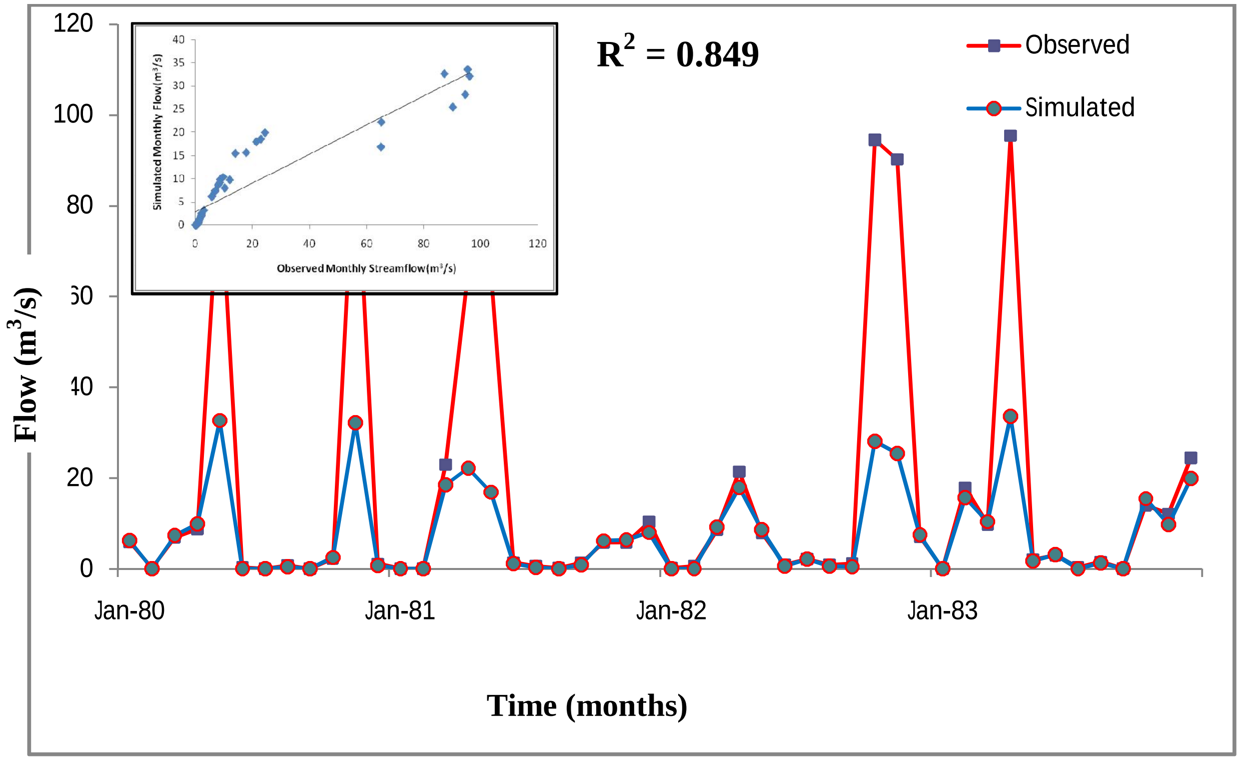


Figure A.10.3 Observed and simulated stream flow for Thiririka River at station 3BD05 with scatter plot showing the correlations during calibration

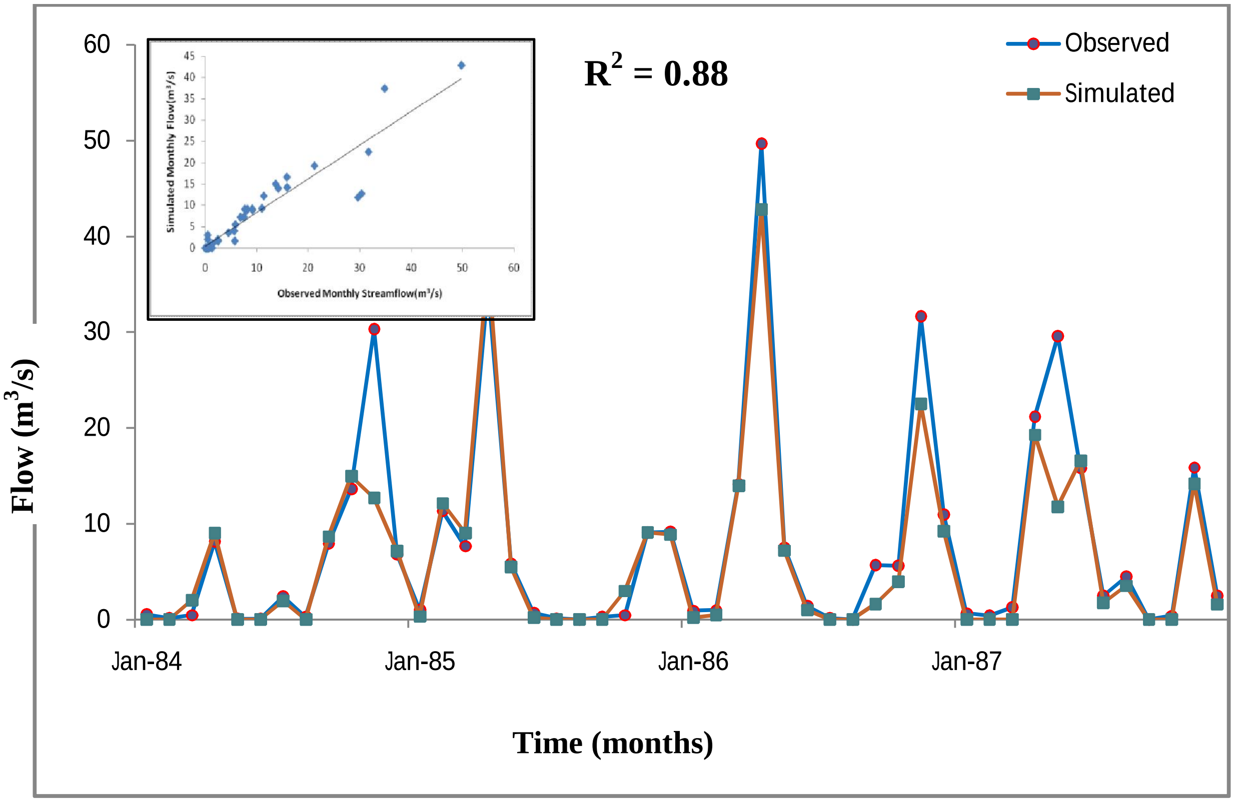


Figure A.10.4 Observed and simulated streamflow for Thiririka River at station 3BD05 with scatter plot showing the correlations during validation

APPENDIX XI Annual Water Demand

Table A.11.1 Supply Delivered in MCM for Reference Scenario

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Coffee Ndarugu	2.3	0	0.3	0.3	2.5	2.3	2.5	2.3
Coffee Thiririka	2.6	0.7	3.9	2.6	2.9	2.4	2.9	2.6
Gatundu B	2.9	1.9	5.3	4.0	5.0	5.3	6.2	6.3
Juja	1.8	0	0.3	0.3	3.1	3.5	3.8	3.9
Nairobi	2.7	0.4	1.9	1.1	0.7	8.3	9	9.5
Premier Bag	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1
Ruiru Town	2.1	1.0	2.1	1.6	1.8	4.3	4.3	4.3
Coffee Ruiru	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Gatundu	4.3	4.8	5.3	6.0	6.7	7.4	8.3	9.3
Kenyatta	0	0.1	0.1	0.2	0.2	0.4	0.5	0.8
Flower Ndarugu	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Flower Thiririka	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

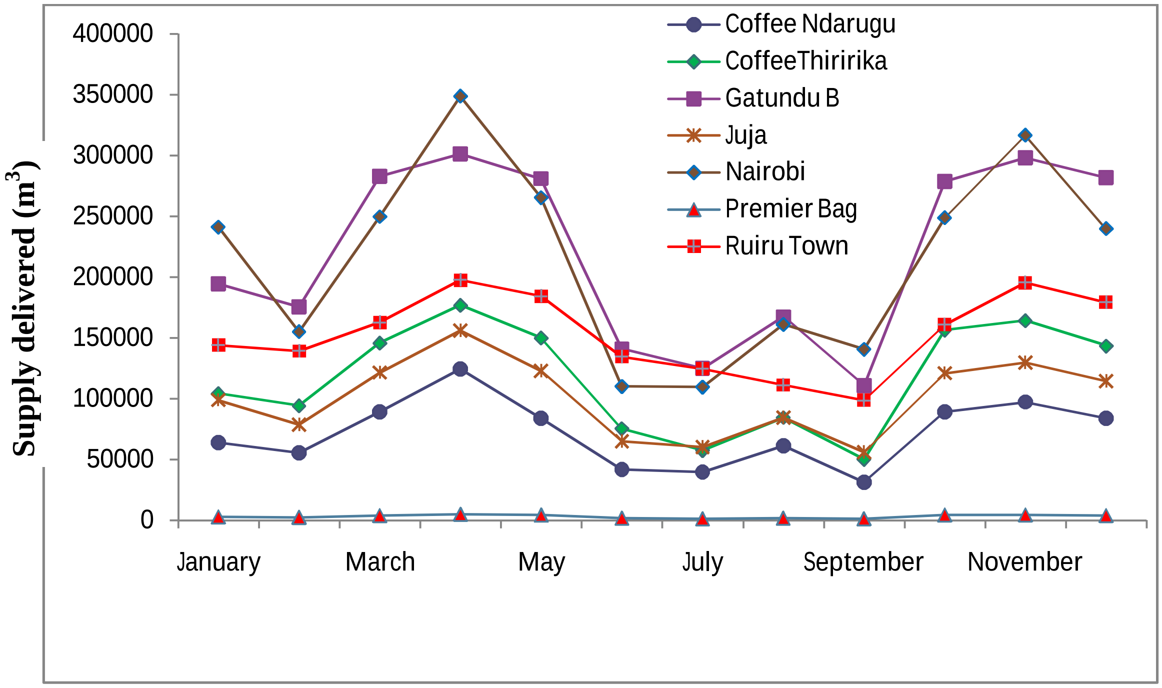


Figure A.11.1 Supply delivered to demand sites during the reference scenario

Table A.11.2 Unmet Demand in MCM for Reference Scenario

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Coffee Ndarugu	1.10	3.36	3.08	3.08	0.85	1.08	0.85	1.10
Coffee Thiririka	1.28	3.264	0	1.29	0.99	1.52	0.99	1.35
Gatundu	0	0	0	0	0	0	0	0
Gatundu B	1.40	2.87	0	1.92	1.68	2.19	2.09	3.02
Juja	0.82	2.95	3.03	3.38	1.04	1.13	1.29	1.83
Kenyatta	0	0	0	0	0	0	0	0
Nairobi	1.30	4.39	3.84	5.79	7.64	1.68	3.03	4.96
Premier Bag	0.04	0.10	0	0.04	0.03	0.06	0.03	0.05
Ruiru	0.87	2.26	1.55	2.53	2.77	0.82	1.43	2.07
Others	0	0	0	0	0	0	0	0

Table A.11.3 Water Demand in MCM for High Population Growth Scenario

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Coffee Ndarugu	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Coffee Ruiru	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Coffee Thiririka	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Gatundu	4.3	5.6	7.4	9.6	12.6	16.6	21.7	28.5
Gatundu B	4.3	5.6	7.4	9.6	12.6	16.6	21.7	28.5
Juja	2.6	3.5	4.5	6.0	7.8	10.2	13.4	17.6
Kenyatta	0	0.1	0.1	0.2	0.2	0.4	0.5	0.8
Nairobi	4.0	5.2	6.9	9.0	11.8	15.4	20.2	26.5
Ruiru Town	2.9	3.8	5.0	6.6	8.6	11.3	14.9	19.5
All Others	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

Table A.11.4 Supply Delivered in MCM for High Population Growth Scenario

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Nairobi	2.7	0.4	2.1	1.5	1.0	11.9	15.1	14.5
Premier Bag	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ruiru	2.1	1.2	2.9	2.5	3.4	9.5	11.1	13.0
Gatundu B	2.9	2.2	7.4	6.5	9.5	9.9	16.2	17.3
Coffee Thiririka	2.6	0.7	3.9	2.6	2.9	1.6	2.9	2.0
Coffee Ndarugu	2.3	0	0.3	0.3	2.5	2.1	2.5	2.0
Juja	1.8	0	0.4	0.5	5.8	7.3	10.0	11.6
Coffee	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5

Ruiru								
Flower Ndarugu	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Flower Thiririka	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Gatundu	4.3	5.6	7.4	9.6	12.6	16.6	21.7	28.5
Kenyatta	0.0	0.1	0.1	0.2	0.2	0.4	0.5	0.8

Table A.11.5 Unmet Demand in MCM for High Population Growth Scenario

Demand Site	**1980**	**1984**	**1988**	**1992**	**1996**	**2000**	**2004**	**2008**
Coffee Ndarugu	1.1	3.4	3.1	3.1	0.8	1.3	0.8	1.4
Coffee Thiririka	1.3	3.3	0	1.3	1.0	2.3	1.0	1.9
Gatundu	0	0	0	0	0	0	0	0
Gatundu B	1.4	3.4	0	3.1	3.2	6.7	5.5	11.2
Juja	0.8	3.5	4.2	5.5	2.0	3.0	3.4	5.9
Kenyatta	0	0	0	0	0	0	0	0
Nairobi	1.3	4.8	4.7	7.5	10.8	3.6	5.1	12.1
Premier Bag	0	0.1	0	0	0	0.1	0	0.1
Ruiru	0.9	2.6	2.1	4.1	5.3	1.8	3.7	6.5
Others	0	0	0	0	0	0	0	0

Table A.11.6 Water Demand in MCM for area under irrigation is reduced by half scenario

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Coffee Ndarugu	3.4	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Coffee Ruiru	7.5	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Coffee Thiririka	3.9	2	2	2	2	2	2	2
Gatundu	4.3	4.8	5.3	6.0	6.7	7.4	8.3	9.3
Gatundu B	4.3	4.8	5.3	6.0	6.7	7.4	8.3	9.3
Juja	2.6	3.0	3.3	3.7	4.1	4.6	5.1	5.7
Kenyatta	0	0.1	0.1	0.2	0.2	0.4	0.5	0.8
Nairobi	4	4.8	5.8	6.9	8.3	10	12	14.4
Ruiru Town	2.9	3.3	3.7	4.1	4.6	5.1	5.7	6.3
All Others	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Table A.11.7 Supply delivered in MCM for Area under irrigation is reduced by half scenario

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Nairobi	2.7	0.4	1.9	1.1	0.7	8.3	9.0	9.5
Premier Bag	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1
Ruiru	2.1	1.0	2.1	1.6	1.8	4.3	4.3	4.3
Gatundu B	2.9	1.9	5.3	4.0	5.0	5.3	6.2	6.3
Coffee Thiririka	2.6	0.3	2.0	1.3	1.5	1.3	1.5	1.3
Coffee Ndarugu	2.3	0	0.1	0.1	1.3	1.2	1.3	1.1
Juja	1.8	0	0.3	0.3	3.1	3.5	3.8	3.9
Coffee	7.5	3.8	3.8	3.8	3.8	3.8	3.8	3.8

Ruiru								
Flower Ndarugu	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Flower Thiririka	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Gatundu	4.3	4.8	5.3	6.0	6.7	7.4	8.3	9.3
Kenyatta	0	0.1	0.1	0.2	0.2	0.4	0.5	0.8

Table A.11.8 Unmet Demand in MCM for Area under irrigation is reduced by half scenario

Demand Site	**1980**	**1984**	**1988**	**1992**	**1996**	**2000**	**2004**	**2008**
Coffee Ndarugu	1.10	1.68	1.54	1.54	0.42	0.52	0.42	0.55
Coffee Thiririka	1.28	1.63	0	0.64	0.49	0.70	0.49	0.64
Gatundu	0	0	0	0	0	0	0	0
Gatundu B	1.40	2.87	0	1.92	1.68	2.19	2.09	3.02
Juja	0.82	2.95	3.02	3.38	1.04	1.13	1.29	1.83
Kenyatta	0	0	0	0	0	0	0	0
Nairobi	1.30	4.39	3.84	5.79	7.64	1.68	3.03	4.96
Premier Bag	0.04	0.10	0	0.04	0.03	0.05	0.03	0.04
Ruiru	0.87	2.26	1.55	2.53	2.77	0.82	1.43	2.07
Others	0	0	0	0	0	0	0	0

Table A.11.9 Unmet Demand in MCM for Environmental Flow Requirement Scenario

Demand Site	**1980**	**1984**	**1988**	**1992**	**1996**	**2000**	**2004**	**2008**
Coffee Ndarugu	1.1	3.4	3.1	3.1	3.1	3.4	3.1	2.8
Coffee Thiririka	1.3	3.3	2.3	2.9	3.3	3.6	2.9	3.3
Gatundu	0	0	0	0	0	0	0	0
Gatundu B	1.4	2.8	2.0	3.6	3.6	5.5	3.6	5.6
Juja	0.8	3.0	3.0	3.4	3.8	4.6	4.7	4.8

Kenyatta	0	0	0	0	0	0	0	0
Nairobi	1.3	4.4	4.3	5.8	7.6	9.2	11.0	12.0
Premier Bag	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ruiru	0.9	2.3	1.6	2.5	2.7	3.8	3.3	4.3
Others	0	0	0	0	0	0	0	0

Table A.11.10 Supply Delivered in MCM for Irrigation Water Quality Constraint Scenario

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Nairobi	2.7	0.4	1.9	1.1	0.7	8.3	9.0	9.5
Premier Bag	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1
Ruiru	2.1	1.0	2.1	1.6	1.8	4.3	4.3	4.3
Gatundu B	2.9	1.9	5.3	4.0	5.0	5.3	6.2	6.3
Coffee Thiririka	2.6	0.7	3.9	2.6	2.9	2.4	2.9	2.6
Coffee Ndarugu	2.3	0	0.3	0.3	2.5	2.3	2.5	2.3
Juja	1.8	0	0.3	0.3	3.1	3.5	3.8	3.9
Coffee Ruiru	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Flower Ndarugu	0.1	0.1	0.1	0.1	0.1	0.133	0.1	0.1
Flower Thiririka	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Gatundu	4.3	4.8	5.3	6.0	6.7	7.4	8.3	9.3
Kenyatta	0	0.1	0.1	0.2	0.2	0.4	0.5	0.8

Table A.11.11 Unmet Demand in MCM for Irrigation Water Quality Constraint Scenario

Demand Site	1980	1984	1988	1992	1996	2000	2004	2008
Coffee Ndarugu	1.10	3.40	3.08	3.08	0.85	1.08	0.85	1.10
Coffee Thiririka	1.28	3.26	0	1.29	0.99	1.52	0.99	1.35
Gatundu	0	0	0	0	0	0	0	0
Gatundu B	1.40	2.87	0	1.92	1.68	2.19	2.09	3.02
Juja	0.82	2.95	3.03	3.38	1.04	1.13	1.29	1.83
Kenyatta	0	0	0	0	0	0	0	0
Nairobi	1.30	4.39	3.84	5.78	7.64	1.68	3.03	4.96
Premier Bag	0.04	0.10	0	0.04	0.03	0.06	0.03	0.05
Ruiru	0.87	2.26	1.55	2.53	2.77	0.82	1.43	2.07
Others	0	0	0	0	0	0	0	0