

**SIMULATION OF WATER SUPPLY AND DEMAND IN KIPKAREN RIVER  
SUB-CATCHMENT OF UPPER NZOIA CATCHMENT**

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**(WRE/G/01-70239/2020)**

**A Research Thesis Submitted in Partial Fulfilment of the Requirements for the  
Award of the Degree of Masters of Science in Water Resource Engineering, of  
Masinde Muliro University of Science and Technology**

**July, 2025**

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## **DEDICATION**

This Thesis is dedicated to the Almighty God and my late mum, Jane.

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I most sincerely acknowledge my supervisors, Dr.Edwin Kanda and Dr. Micah Mukolwe, who assisted mw with research conceptual review and also walked me through the journey of my M.Sc research study. Secondly, I acknowledge my family for being supportive both morally and financially during the entire prost-graduate study duration. Finally, I acknowledge Dr. (Eng) Jared Okungu) and y fellow M.Sc students at Masinde Muliro University of Science and Technology for peer review work. Finally, I acknowledge my colleagues at place of work for their understanding and encouragements.

## ABSTRACT

Water allocation and planning have faced significant challenges globally, particularly in sub-Saharan Africa, where rapid population growth, climate change, and insufficient infrastructure exacerbate existing pressures. This study focused on the Upper Nzoia Catchment in Kenya, specifically the Kipkaren Micro-Catchment, which is experiencing rising water demand and variability in supply. The primary objective was to simulate water supply and demand, assess current availability, model future scenarios using the WEAP Model, and determine optimal allocation strategies for the period 2020–2050. The study is grounded in theoretical frameworks including Integrated Water Resources Management (IWRM), Simulation and Modeling Theory, and Decision Support Systems (DSS). Using a mixed-methods approach, the research collected data on hydrological conditions and sector-specific water demands—agriculture, domestic use, industry, and livestock. This data was integrated into the WEAP model, which was calibrated using historical streamflow records to improve accuracy between simulated and observed results. Scenario analysis included a Reference Scenario, High Population Growth, Increased Agricultural Capacity, Extended Dry Climate, and Wet Climate Sequence. These scenarios accounted for land use changes, climate variability, and population growth trends. The model analysis included evaluation of key parameters and statistical comparisons across scenarios. Results showed strong model performance, with high Nash-Sutcliffe efficiency,  $r^2$ , and correlation coefficients during both calibration (1990–2000) and validation (2001–2010). Streamflow analysis (1959–2019) revealed high variability, with a projected peak flow of 554.87 m<sup>3</sup>/s in 2024 and minimums down to 6.35 m<sup>3</sup>/s. Seasonal variation was evident, with October showing peak flows. In 2019, domestic water demand was approximately 9,796 m<sup>3</sup>/day for a population of 287,000, while agricultural demand reached about 100,200 m<sup>3</sup>/day. The study found that total demand exceeds average availability during dry periods. Scenario projections showed demand may rise from 71.5 million m<sup>3</sup> in 2019 to about 114.3 million m<sup>3</sup> by 2050, particularly under drier climate or high-growth scenarios. These findings emphasize the impact of seasonal and climate-driven variability and the risks of water shortages without adaptive planning. To address these challenges, integrated strategies are recommended, including water conservation measures, rainwater harvesting infrastructure, and broader implementation of IWRM. The WEAP model proved effective for simulating water dynamics and informing future planning. The study contributes to the broader understanding of water resource management in the region and highlights the need for further research into remote sensing, adaptive decision support systems, policy evaluation, and the socio-economic implications of water scarcity.

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## **ABBREVIATIONS AND ACRONYMS**

CMS	Cubic Meter per Second
DEM	Digital Elevation Model
DIM	Domestic, Institutional and Municipal
DSS	Decision Support System
EPA	Environmental Protection Agency
GIS:	Geographical Information System
GWP	Global Water Partnership
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
ITCZ	Inter-Tropical Convergence Zone
IWA	International Water Association
IWRM	Integrated Water Resources Management
MAE	Mean Absolute Error
MCDM	Multi-Criteria Decision Making
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow
MODSIM	Modeling and Simulation
MULINO	MULTi-sectoral, Integrated and Operational DSS
NSE	Nash-Sutcliffe Efficiency
PAWDP	Partnership for Africa's Water Development Programme
RIBASIM	River Basin Simulation Model

RMSE:	Root Mean Square Error
STDEV	Standard Deviation
SWAT	Soil and Water Assessment Tool
UNECE	United Nations Economic Commission for Europe
WARMA	Water Resources Management Authority
WBalMo	Water Balance Model
WEAP	Water Evaluation And Planning

## OPERATIONAL DEFINITION OF TERMS

*Decision Support Systems:* Mathematical models that consist of quantitative and qualitative relationships which can simulate, predict and translate outputs from various IWRM hydrodynamic inputs into useful information for decision making by water resources planners and policy makers.

*Demand Site:* A set of water users that share a physical distribution system, that are all within a defined region, or that share an important withdrawal supply point.

*Environmental Flow:* The minimum river flow required to sustain ecosystems and downstream communities. In your study, it's modeled as a non-negotiable demand in WEAP to ensure ecological sustainability alongside human use.

*Hydrological Catchment:* A land area with defined geographic boundaries that captures precipitation and partitions it into evapo-transpiration, runoff to surface water and infiltration to groundwater.

*Hydrological Models:* These are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes.

*Increased Agricultural Capacity:* Denotes the potential for enhanced irrigation and crop productivity from better water availability and allocation. Through WEAP scenarios, it reflects shifts in land use, efficiency, and seasonal demand planning.

*Reference Scenario:* A scenario that represents the changes that are likely to occur in the future, in the absence of any new policy measure. Sometimes called a "business as usual" scenario.

*Sensitivity:* Changes that occur in a scenario because of different socio-economic, hydrologic or technology assumptions, rather than because of different policies.

*Simulation and Modeling:* A way that planners and engineers attempt to predict impacts of possible design, management and operation policies or decisions. Models are computer-based tools that are designed to estimate how important various uncertain assumptions and data can achieve desired outcome or impact through simulation.

*Water Allocation:* The amount of water made available to upstream, midstream and downstream users, including the ecological purposes.

*Wet Sequence:* A period of unusually high rainfall over consecutive years in the Kipkaren River Sub-Catchment, influencing runoff and storage. It's crucial in your WEAP simulations for modeling hydrological variability and stress-testing allocation strategies.

# CHAPTER ONE

## INTRODUCTION

### 1.1 Background of the Study

#### Water

Water allocation and planning have emerged as pressing global challenges, driven by rising water demand and uneven supply - particularly due to population growth and the intensification of agricultural production (International Water Management Institute, 2021). Nowhere is this more acute than in sub-Saharan Africa, where the combination of rapid demographic expansion, climate change, and inadequate infrastructure has created a widening gap between water supply and demand. This imbalance is further aggravated by limited storage capacity, inefficient irrigation systems, and competition among agricultural, industrial, and domestic sectors. The region also grapples with weak water governance, fragmented policies, and economic limitations that hinder investment in water supply systems. Global institutions, including the United Nations through its *World Water Development Report* (United Nations, 2023) and the United Nations Economic Commission for Europe (UNECE) via its *Global Water Conventions* (UNECE, 2023), have underscored the urgency of implementing integrated water resource management strategies. These initiatives stress the importance of aligning water supply with growing and often competing demands, ensuring sustainable, efficient, and equitable water use across all sectors.

Efficient management of water resources is a crucial matter on a global scale, driven by an array of factors including high growth of population, suburbanization, economic growth, and environment variations (World Economic Forum, (2023).). Integrated-Water Resources-Management (I.W.R.M.) has emerged as a inclusive framework designed to address these multifaceted challenges by promoting a holistic approach to water management. This approach seeks to balance the economic, environmental and social needs of communities by coordinating the administration of water as a resource across a number of sectors and scales. IWRM highlights the significance of focusing on the entire water cycle, beginning with the point of intake/source to consumption, and integrating the management of land and water resources to achieve sustainable outcomes (The World Bank, 2018).

International organizations such as the International-Water-Association (IWA) plus the Global-Water-Partnership (GWP) play pivotal roles in advancing global water administration approaches. The IWA is dedicated to advancing the science and practice of water administration through innovation, research, and technology. It provides a platform for professionals to share knowledge, develop new solutions, and collaborate on water-related issues (International Water Management Institute, 2023). The IWA's initiatives often focus on improving water treatment technologies, optimizing water distribution systems, and fostering sustainable practices across various sectors (World Bank Group, 2016).

Similarly, the GWP works to facilitate unified approaches to water resources administration and management by fostering collaboration among governments, organizations, and stakeholders. The GWP's mission is to promote sustainable water management practices through advocacy, capacity-building, and the dissemination of best

practices (International Water Management Institute, 2023). One of its key roles is to support the development and implementation of decision support systems (DSS) that leverage data, modeling, and forecasting tools to improve water management. These systems are crucial for optimizing water allocation, predicting future water needs, and addressing challenges related to water scarcity and quality (World Bank Group, 2016).

The need for effective decision support systems in water management is underscored by the increasing complexity of water-related challenges. As seasonal variations of climate impacts precipitation patterns, raises the frequency of adverse weather events, and influences water availability, decision support systems are crucial for adapting to these changes (World Economic Forum, 2023). DSS tools help decision-makers to analyze complex data, simulate different scenarios, and develop strategies that enhance water resilience and sustainability. By adopting enhanced technological approaches, for instance the G-I-S, remote sensing technologies, and hydrological modeling, such systems enhance more informed including proactive water management decisions (United-Nations-Educational,-Scientific & Cultural Organization, 2024).

Worldwide, there is an increasing appreciation of the necessity to adopt a comprehensive and integrated water management strategies that is capable of responding to the diverse and often unpredictable nature of water and climate resources. The adoption of Integrated Water Resources Management (IWRM) and the implementation of decision support systems reflect a broader commitment to addressing water challenges through coordinated and innovative approaches (United-Nations-Educational, Scientific & Cultural Organization, 2019). While the populations continue to grow and climate impacts become more pronounced, the importance of these frameworks and tools will only increase,

highlighting the need for continued investment in water management research, technology, and capacity-building at the global level (U.S. Geological Survey, 2023).

In Europe, advanced water management practices are evident in countries such as the Netherlands and Germany. The Netherlands, renowned for its sophisticated flood management systems, employs advanced decision support tools to manage its intricate water networks. Germany's approach includes integrated water management strategies that utilize DSS to effectively manage water supply and demand effectively (UNESCO, 2016). Among the European Union, these efforts are supported through regulations like the Water Framework Directive, which mandates member-states to attain better status of water availability and quality, including implementation of effective and efficient anagement practices (Town-of-Cary, 2017).

Asia presents a diverse range of water management challenges and solutions. According to Chen and Tsai (2017), Japan has implemented cutting-edge technology and decision support systems to manage water resources and mitigate the impacts of natural disasters like floods and tsunamis. China, with its significant water scarcity issues, has invested in large-scale water transfer projects and advanced modeling tools to address its water allocation challenges (Li *et al.*, 2018). These efforts highlight the region's anticipatory strategy for combining technology, together with strategic planning in water management

South America also faces substantial water management issues, particularly in countries like Brazil and Argentina. Brazil's efforts to manage the Amazon Basin, a crucial yet vulnerable water resource, include the development of integrated management systems and advanced DSS to address deforestation and water quality issues (Jain & Singh, 2023). In Argentina, efforts to improve water management in the Paraná Basin involve using

decision support tools to enhance water allocation and quality management, reflecting a broader regional commitment to addressing water challenges through innovative solutions (Borgomeo *et al.*, 2018).

In the United States, Canada and North America, sophisticated frameworks have been developed for water management supported by advanced decision support systems. The United States Environmental-Protection-Agency (EPA) and Canada's Ministry of Environment and Climate Change have implemented comprehensive policies and tools to manage water resources, address contamination issues, and ensure sustainable usage. These countries use modeling and forecasting tools to inform water management decisions and policies, demonstrating their commitment to effective and data-driven water resource management (Runyon, 2019).

In Africa, water resource management presents a complex set of challenges that are deeply intertwined with the continent's unique climatic, economic, and socio-political conditions. Heightened increase in population, in addition to change of environmental conditions, has exacerbated issues related to water availability and quality (Teague *et al.*, 2021). Many African countries face severe water scarcity, inadequate infrastructure, and inefficient water management practices, which hinder their ability to ensure sustainable water resources for their populations.

The IWRM is widely considered in a number of African countries as a strategy to address these challenges. According to Huber *et al.* (2019), this approach seeks to manage water resources in a way that balances environmental, social, and economic needs. Organizations such as the Global-Water-Partnership (GWP) and the Partnership for Africa's Water Development Programme (PAWDP) have been instrumental in promoting IWRM

practices across the continent. The GWP supports initiatives aimed at improving water governance and integrating water management at different societal levels. The PAWDP works with the aim of enhancing water resource management through capacity-building, policy development, and investment in water infrastructure (Phan *et al.*, 2021).

South Africa has made notable progress in water management through its implementation of the National Water Act, which highlights justifiable and reasonable water use. The country's water management strategies include the growth of comprehensive water resource plans and the utilization of decision support systems (DSS) to optimize water allocation and quality management. The establishment of institutions such as the Department of Water, Hygiene and Sanitation reflects a commitment to addressing water challenges through regulatory frameworks and technological solutions (Loucks *et al.*, 2017).

Morocco is another African nation that has made significant strides in water resource management. The country has invested in major water infrastructure initiatives, including the building of dams and the development of irrigation networks, to address water scarcity and support agricultural productivity (Wang *et al.*, 2021). Morocco's National Water Plan aims to improve water efficiency, improve quality of water, and encourage justifiable water exploitation through integrated control practices (Rad *et al.*, 2017).

Egypt, with its reliance on the Nile River, faces unique challenges related to water management. The country has implemented various initiatives to manage water resources effectively, including the building of the Aswan High Dam, plus development of irrigation and drainage networks (Alcamo, 2019). Egypt's water use approaches look onto

optimizing possible use of available water and climatic resources, improving water quality, in addition to addressing the impacts of climate change.

Ethiopia has also been proactive in addressing water resource challenges through the development of infrastructure and policies. The construction of the Grand Ethiopian Renaissance Dam is a significant project aimed at improving water storage and generating hydroelectric power (Sepahvand *et al.*, 2019). Ethiopia's water management efforts are supported by national policies and strategies that focus on improving access to water, enhancing water quality, and promoting sustainable water use (Ahmad & Verma, 2018).

Tanzania has made efforts to improve water management through initiatives such as National-Water-Policy, emphasizing on integrated water resources management and community participation. The country's approach includes investing in water infrastructure, improving data collection, and implementing decision support tools to enhance water management and address issues such as water scarcity and quality (Xiang *et al.*, 2021).

Nigeria and Ghana are also working to address water management challenges. In Nigeria, efforts are underway to advance water infrastructure plus implement integrated water management practices to handle matters akin to scarcity of water and pollution. Ghana has focused on improving water access and quality through improvement of supply of water systems and the adoption of IWRM principles (Loucks & Van Beek, 2017).

Several management water challenges are faced by the sub-Saharan African and South. Subsequently, countries like Malawi, Mozambique, and Bangladesh grapple with issues related to water supply and demand due to limited access to advanced decision support systems and inadequate infrastructure (Chopra & Ramachandran, 2021). These nations

often experience difficulties in managing water resources effectively due to insufficient data, lack of technology, and limited technical expertise. For instance, in Kenya, water availability is constrained by declining water volumes caused by climatic variations, per-capita growth, and altering land-uses (Herman *et al.*, 2020). The country faces significant challenges due to climate change, which exacerbates water shortages and impacts sustainable development. According to the World Bank, Kenya is classified as water-scarce, with only 647 m<sup>3</sup> of renewable freshwater available per capita annually, far below the threshold for water scarcity. The Water Act of 2002 has prompted improvements in Kenya's water management sector, including the establishment of Catchment Area Advisory Committees (CAACs) to enhance water management at the catchment level. However, the country continues to face challenges in water resource allocation and development, with only 15% of safe water resources currently developed. Initiatives like the Kakamega County Integrated Development Plan and partnerships with the World Bank aim to address these issues through improved access to clean water and infrastructure development (Jain & Singh, 2023).

While advanced decision support systems and integrated water management practices have made significant progress in many parts of the world, developing nations still face substantial challenges. Addressing these issues requires global collaboration, investment in technology, and capacity-building to ensure that effective water management solutions are accessible and applicable in all regions (Loucks *et al.*, 2017).

### **1.1.1 The Use of Decision Support Systems for Water Supply and Demand**

Decision Support Systems (DSS) have become crucial tools in the management of water supply and environmental systems, providing valuable insights and facilitating informed

decision-making in the face of increasing complexity and uncertainty. According to Nhemachena *et al.* (2020), these systems integrate data, analytical models, and user interfaces to assist policymakers, planners, and managers in fronting effective choices regarding water resources, including environmental sustainability.

Decision Support-Systems have pivotal role in optimizing water supply management by enabling comprehensive analysis and scenario planning. A, important benefits of DSS is the capacity to integrate various data-related information sources, including hydrological data, climate forecasts, and socio-economic factors. This integration allows for a more accurate assessment of water availability and demand, helping to identify potential shortages and opportunities for resource optimization (Duan *et al.*, 2019).

For example, models like the WEAP platforms provide a robust framework for simulating different water management scenarios. According to Schneider *et al.* (2019), WEAP permits users to analyze the influence of a number of policies, land-use variations, and climate conditions on water resources. By evaluating different scenarios, decision-makers can develop strategies to balance water supply and demand, improve water allocation efficiency, and enhance resilience to potential future challenges (Yang *et al.*, 2018).

In addition to water supply management, DSS are essential for effective environmental management. These systems support the monitoring and analysis of environmental variables such as water quality, ecosystem health, and pollutant levels. By integrating environmental data with predictive models, DSS can help identify trends and assess the influence of conventional activities of upstream communities, plus natural events on environmental systems (Yao *et al.*, 2021).

For instance, models like the Soil-and-Water-Assessment-Tool (SWAT) are utilized in order to simulate the impact of land-use changes together with agricultural practices on water quality and quantity. According to Sahoo *et al.* (2020), SWAT helps in understanding how different land management practices affect runoff, sedimentation, and nutrient loading, thereby guiding the development of sustainable land and water management strategies.

Decision Support Systems also facilitate integrated management approaches by linking water and environmental management with broader socio-economic factors (Kandera & Výleta, 2020). Integrated models consider the interplay between water resources, land use, and economic activities, enabling a holistic approach to resource management. This integration helps in addressing complex challenges such as managing water resources in the face of urbanization, environmental variations, and competing demands from agriculture and industry (Leong & Lai, 2017).

Models like the Integrated Valuation of Ecosystem-Services-and-Tradeoffs (In\_VEST) tool provide a framework for evaluating the tradeoffs among divergent land\_use scenarios and the impacts on ecosystem services. According to Al-Juaidi and Al-Shotairy (2020), InVEST helps policymakers and planners to make informed decisions that balance environmental conservation with economic development.

The use of DSS in water supply and environmental management supports more informed decision-making and policy development. These systems provide treasured intuitions into the potential outcomes of diverse management strategies, helping to identify the most effective approaches to achieve desired objectives. By incorporating stakeholder inputs and considering a range of scenarios, DSS facilitate the creation of effective management

strategies that can adapt to evolving conditions and new challenges (Nhemachena *et al.*, 2020).

Despite their benefits, the implementation of DSS in water supply and environmental management faces several challenges. These include data limitations, model complexity, and the need for interdisciplinary collaboration (Duan *et al.*, 2019). Tackling these challenges necessitates continuous efforts to improve data quality and strengthen model accuracy, and foster collaboration among stakeholders.

Future developments in DSS will likely focus on cutting-edge technologies like artificial intelligence, machine learning, and real-time data analysis. These advancements have the potential to further enhance the capabilities of DSS, providing more accurate predictions, optimizing decision-making processes, and supporting more effective management of water and environmental resources (Sahoo *et al.*, 2020).

### **1.1.2 The Water Supply and Demand Situation in Kenya**

Kenya faces a complex array of challenges related to water resource management and demand, driven by its variable climate, rapid population growth, and pressures from economic development. Water availability is both spatially and temporally uneven, with significant disparities between regions and across seasons. Geographically, water resources are unequally distributed across the country, with arid and semi-arid areas facing chronic and acute water scarcity (Mulwa *et al.*, 2021). Temporally, this disparity is compounded by Kenya's heavy reliance on unpredictable and seasonal rainfall patterns, which often lead to periodic shortages and droughts, particularly in areas with low annual precipitation (Chepyegon & Kamiya, 2018).

As the population continues to grow and urbanize, water demand rises across all sectors - domestic, industrial, and agricultural - further intensifying pressure on limited water supplies and aging infrastructure (Kou *et al.*, 2018). Projections suggest that demand will increasingly outpace supply in many parts of the country, especially under climate change scenarios and expanding urban development. Some regions are expected to face more severe deficits than others, necessitating spatially targeted interventions.

Kenya's water infrastructure also struggles to meet current needs, *let alone* future demands. Urban areas frequently face intermittent or rationed water supply, while rural communities often rely on unreliable or unsafe sources (Ondigo *et al.*, 2018). Climate variability - through shifting rainfall patterns, prolonged droughts, and more frequent extreme weather events - further exacerbates water supply-demand mismatches (Nyilitya *et al.*, 2020). Addressing these challenges requires water resource management solutions that are both spatially explicit and time-sensitive (Omonge *et al.*, 2020).

Several major initiatives in Kenya stand to benefit from the use of Decision Support Systems (DSS) to improve water planning. For example, in the Nzoia Catchment, DSS can be used to evaluate current water availability and future demand across different locations and time periods, taking into account population growth, land use changes, and climate variability (Juma *et al.*, 2022). This approach supports the identification of areas at high risk of water stress and the development of tailored allocation strategies for competing water users, including agriculture, domestic needs, and industry (Richards & Syallow, 2018).

Urban water systems in Kenya present another important opportunity for DSS applications. Rapid urbanization is leading to concentrated spikes in demand, making it essential to

forecast future needs accurately and plan infrastructure accordingly. DSS tools can assist in designing systems that improve efficiency, reduce losses, and expand access to meet projected demands over time (Njora & Yilmaz, 2021). These tools also enable real-time monitoring and performance analysis to enhance operational decision-making (Mumbi *et al.*, 2021).

In agriculture, DSS can promote more efficient water use by helping farmers optimize irrigation schedules based on weather forecasts, soil moisture levels, and crop requirements. This not only improves productivity but also reduces water waste (Nyilitya *et al.*, 2020). Moreover, DSS can simulate long-term climate impacts on water availability and agricultural output, informing adaptive strategies for sustainable farming in water-scarce regions (Chepyegon & Kamiya, 2018).

Integrated catchment management is another area where DSS can provide value. These systems facilitate stakeholder participation by presenting geospatial visualizations and scenario models that clarify the consequences of various policy or management decisions (Omonge *et al.*, 2020). They also help evaluate the environmental impacts of water management actions on ecosystems and biodiversity (Juma *et al.*, 2022). Evidence generated through DSS can further support the formulation of effective water regulations and policies (Mulwa *et al.*, 2021).

The study's objectives aimed to address key aspects of water resource challenges in the Upper Nzoia Catchment, with a focus on the Kipkaren River. By assessing current and projected water availability and demand, simulating various spatial and temporal scenarios using the WEAP Model, and evaluating optimal allocation strategies, the study provides an in-depth understanding of the region's water dynamics. Ultimately, the goal was to offer

actionable recommendations for sustainable water resource management and policy formulation, grounded in scenario-based assessments. These findings are intended to guide effective and forward-looking water practices that balance present needs with future risks across both space and time.

## **1.2 Problem Statement**

Effective water allocation and planning remain pressing global challenges, particularly in sub-Saharan Africa, where rapid population growth, climate variability, and limited infrastructure severely constrain sustainable water resource management. In response, prominent organizations such as the United Nations (UN), United Nations Economic Commission for Europe (UNECE), World Bank, International Water Management Institute (IWMI), and the Food and Agriculture Organization (FAO) have emphasized the urgent need for sustainable water governance, innovative planning tools, and inclusive stakeholder engagement.

In Kenya, the Upper Nzoia Catchment - specifically the Kipkaren River sub-catchment - illustrates these challenges acutely. The area is vital for local agriculture, domestic water supply, and ecological integrity, yet it faces increasing demand amid variable and uncertain water supply conditions. Current water management strategies in the region are constrained by limited understanding of supply-demand dynamics, inadequate forecasting, and dependence on outdated or fragmented data. This has led to inefficiencies, overuse, and growing competition among users, all of which threaten long-term water sustainability.

A critical gap exists in the availability of detailed, long-term hydrological data and the use of predictive models that can support forward-looking water resource planning. Without such tools, it is difficult to accurately project future water availability or to assess the

impact of various socio-economic and climate scenarios. This shortfall limits the capacity of decision-makers to design and implement responsive and adaptive water management interventions.

To address this gap, the present study applies the Water Evaluation and Planning (WEAP) Model to the Kipkaren River sub-catchment. The model enables simulation of current water supply and demand dynamics, scenario analysis for future conditions, and evaluation of optimal allocation strategies. Through this approach, the study seeks to generate a comprehensive understanding of the region's water resource trends and provide decision-support information tailored to both present and anticipated challenges.

The absence of such an in-depth, systems-based analysis hampers effective policy-making and implementation. Consequently, this research aims to fill the existing knowledge void by delivering evidence-based, context-specific recommendations that can inform policy and practice in the Upper Nzoia Catchment.

Ultimately, the study's objectives are to assess the spatial and temporal dynamics of water availability and demand, simulate future scenarios using WEAP, and recommend actionable and sustainable water management strategies. These recommendations are intended to guide the efficient and equitable use of water resources, addressing both current and emerging challenges in the catchment.

### **1.3 Research Objectives**

#### **1.3.1 Main Objective**

The main objective was to simulate Water Supply and Demand in Kipkaren River Sub-Catchment of Upper Nzoia Catchment.

### 1.3.2 Specific Objectives

This study had the following specific objectives:

1. To determine current water **availability** and demand in the River Sub-Catchment of Upper Nzoia Catchment.
2. To simulate the implications of various **scenarios** using the WEAP Model.
3. To determine optimal water **allocation** within the catchment using the WEAP Model.

### 1.4 Research Questions

1. What is the current status of water availability and demand in the Kipkaren River Sub-Catchment of Upper Nzoia Catchment?
2. How can different scenarios impact water supply and demand in the Kipkaren River Sub-catchment of Upper Nzoia Catchment., as simulated using the WEAP Model?
3. What are the optimal water allocation strategies within the Upper Nzoia Catchment based on the WEAP Model simulations?

### 1.5 Significance of the study

This research-study would significantly enhance an understanding of water supply-and-demand in the KIpkaren River Sub-Catchment of Upper Nzoia Catchment. By providing a thorough assessment of current water availability and demand, the research will reveal critical insights into the existing conditions and challenges facing the region.

Simulating various scenarios using the WEAP Model will be pivotal for future planning and decision-making. The ability to explore and predict how different factors might impact water supply and demand will enable stakeholders to anticipate potential problems and

develop strategies to address them proactively. This forward-looking approach is essential for effectively managing water resources in light of changing conditions and uncertainties.

Determining optimal water allocation strategies through the WEAP Model simulations will contribute to more efficient and equitable distribution of water within the catchment. By identifying the best practices for allocating water resources, the study will help identify and ensure that the needs of various users are met while maintaining ecological balance and supporting the resilience of the water system.

The study's recommendations for sustainable water resource management and policy-making will provide actionable strategies based on available data and model simulations. These recommendations will be invaluable for policymakers, stakeholders, and local communities, offering a substance for well-versed decision making plus efficient organization approaches focused on fundamental necessities of Upper Nzoia Catchment.

### **1.6 Scope of the study**

This study focuses on assessing water supply and demand dynamics within the Kipkaren River Sub-Catchment, a component of the Upper Nzoia Catchment. Using the WEAP Model, the research analyzes baseline conditions and simulates future scenarios to evaluate the implications of land use change, climate variability, and population growth on water availability and allocation. The simulation period spans **2020 to 2050**, in alignment with the data inputs and defined scenario assumptions.

The analysis is geographically limited to the Kipkaren River Sub-Catchment, and the model outputs, conclusions, and recommendations are based solely on biophysical and socioeconomic characteristics relevant to this area. As such, the findings are intended to support localized water resources planning and policy decision-making within the Upper

Nzoia Catchment. No extrapolation beyond the 2020–2050 time frame is made, and all projections adhere strictly to the constraints and limitations of the modeled period.

### **1.7 Limitations of the Study**

The study encountered several limitations that influenced the scope and depth of its findings. One key challenge was the absence of comprehensive time series data, which constrained the ability to analyze long-term trends in water supply and demand. To overcome this, the research team utilized the best available datasets, complemented by historical records and field surveys. Where data gaps existed, interpolation techniques were applied to enhance the dataset and support reliable analysis.

Another limitation arose from the assumptions and simplifications required by the WEAP Model, which may not fully reflect the complexity of real-world hydrological systems. To address this, the study applied a comparative approach, evaluating multiple scenarios to reflect different conditions and assumptions, thereby strengthening the robustness of the conclusions drawn.

The study's temporal and spatial coverage also presented limitations, as it could not capture every possible variation in water availability and demand across all seasons and locations. To minimize this constraint, both short-term and long-term data were considered, and the spatial boundaries of the study were clearly defined to capture the key characteristics of the catchment. Additionally, a diverse set of scenarios was modeled to account for potential future developments and uncertainties.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

#### **2.1 Introduction**

This chapter includes a number of sections that explain the theoretical foundation of this research. Firstly, a theoretical review evaluates relevant theories supporting the variables studied within the context of the identified research problem. Next, a conceptual review presents the research variables identified and defined by various research components. An empirical review is then detailed, analyzing previous studies related to the constructs of the study, highlighting key findings, points of difference, and identifying gaps that may inform and necessitate the current study. These gaps are summarized, and finally, a conceptual framework is presented, identifying the variables in a summary table and demonstrating the relationships between them.

#### **2.2 Theoretical Review**

This study is motivated by established theoretical frameworks that aim to clarify the underlying phenomena related to Water Supply and Demand. Firstly, it examines the Integrated Water Resources Management (IWRM) Theory. Next, it explores the Simulation and Modeling Theory in Hydrology. Lastly, the Decision Support Systems (DSS) Theory in Water Management. These theories provide the foundation for this study.

##### **2.2.1 Integrated Water Resources Management (IWRM) Theory**

The Integrated Water Resources Management (IWRM) is promoted by organizations like the Global Water Partnership (GWP), which has been pivotal in advocating for a holistic approach to managing water resources (Chepyegon & Kamiya, 2018).

IWRM posits that water resources should not be managed in isolation. Instead, it advocates for an integrated approach that considers the interconnections between water, land use, agriculture, industry, and ecosystems. This means that water management decisions should account for their impacts on all related sectors and vice versa, ensuring that actions in one area do not negatively affect another (Loucks & Van Beek, 2017). This perspective is supported by Bhave *et al.* (2018), who emphasize that holistic management is crucial for addressing the multifaceted challenges of water resource management effectively.

A core tenet of IWRM is the involvement of all relevant stakeholders in water management processes. This includes governments, local communities, private sector actors, and non-governmental organizations. The theory asserts that effective water management requires the input and collaboration of these diverse groups to reflect multiple perspectives and needs, leading to more equitable and sustainable outcomes (Mendoza *et al.*, 2018).

IWRM also emphasizes that water management must be sustainable, ensuring that water resources are available for future generations while meeting current needs. It focuses on equity, ensuring that water resources are distributed fairly among different users and communities. This, according to Bhave *et al.*, 2018, involves balancing environmental conservation with the needs of various social and economic groups.

The theory advocates for integrated planning and management practices that coordinate water resources with broader land use, economic, and environmental planning. Emphasized by Loucks *et al.*, 2017, this includes developing cross-sectoral policies and strategies that address water issues within the context of overall regional or basin-wide management plans.

However, according to Rad *et al.* (2017), the complexity of IWRM can lead to challenges in coordination and conflict resolution among diverse stakeholders. Implementing IWRM effectively requires substantial data, resources, and institutional support, which may be lacking in some regions. This complexity often leads to difficulties in practical implementation and maintaining effective communication among stakeholders.

In the current study, IWRM provides a framework for assessing water availability and demand in the Kipkaren River within the Upper Nzoia Catchment. The researcher can use IWRM principles to integrate various factors affecting water resources, simulate different scenarios, and develop sustainable management strategies. By applying IWRM, the researcher will ensure that the study considers the holistic and participatory aspects of water management, ultimately leading to more effective and equitable recommendations.

### **2.2.2 Simulation and Modeling Theory in Hydrology**

Simulation and modeling theory in hydrology is supported by researchers such as Loucks and van Beek (2017), who have explored the use of mathematical models to simulate hydrological processes and predict water resource.

The theory posits that mathematical models can accurately represent hydrological processes such as water flow, distribution, and quality. These models use equations and algorithms to simulate how water behaves under different conditions, allowing for predictions of future water dynamics (Tayfur, 2017). This viewpoint is supported by Borgomeo *et al.* (2018), who demonstrate the efficacy of mathematical models in managing and forecasting water resources.

Simulation theory emphasizes the use of models to evaluate different scenarios and their impacts on water resources. By simulating various conditions such as changes in land use,

climate, or management practices, researchers and decision-makers can understand potential outcomes and identify optimal strategies for managing water resources (Phan *et al.*, 2021).

The theory supports the use of modeling as a decision support tool. Models provide valuable insights and forecasts that help in making informed decisions about water management. This involves assessing the potential effects of different management strategies and selecting the most effective ones based on simulated outcomes (Li *et al.*, 2018).

Another postulation is that models can capture the dynamic nature of hydrological systems, including how they respond to changes over time. This dynamic analysis helps in understanding how water resources will evolve under different scenarios and over various time scales (Jain & Singh, 2023).

However, according to Jain and Singh (2023), model uncertainty and data limitations are significant challenges. Models, according to Leong & Lai, 2017) rely on assumptions and input data, which can introduce errors. Additionally, developing accurate models requires extensive calibration and validation, which can be resource-intensive (Yao *et al.*, 2021). These limitations can affect the reliability of predictions and may necessitate additional resources to ensure model accuracy.

In the current study, simulation and modeling theory forms the basis for using the WEAP model to simulate water supply and demand dynamics in the Kipkaren River . The researcher will apply this theory to assess current water availability, explore different scenarios, and determine optimal water allocation. By leveraging simulation and modeling

principles, the researcher will gain insights into potential outcomes and make informed recommendations for water resource management.

### **2.2.3 Decision Support Systems (DSS) Theory in Water Management**

The theory of Decision Support Systems (DSS) in water management is advanced by researchers such as Herman *et al.* (2020), who have explored how DSS can enhance decision-making processes through the integration of data, models, and user interfaces.

DSS theory postulates that effective decision support systems integrate diverse data sources to provide a comprehensive view of water management issues. This integration includes data on water availability, demand, quality, and various environmental and socio-economic factors (Garrick *et al.*, 2017). This perspective is supported by Alcamo (2019), who highlights that integrating diverse data enhances decision-making accuracy and relevance.

The theory emphasizes the use of analytical models within DSS to simulate and analyze water management scenarios. By incorporating models, DSS can provide detailed insights into the impacts of different strategies and help evaluate the effectiveness of various management options (Schneider *et al.*, 2019). A key postulation is that DSS should have user-friendly interfaces that allow stakeholders to interact with the system effectively. This includes inputting data, exploring different scenarios, and interpreting results. The theory asserts that effective user interfaces are crucial for ensuring that the system meets the needs of its users and facilitates informed decision-making (Xiang *et al.*, 2021).

DSS theory supports the idea that these systems help in making complex decisions by providing valuable insights and scenario analyses. DSS enables users to assess the potential outcomes of different management strategies and make decisions based on comprehensive, data-driven insights (Herman *et al.*, 2020). However, according to Ahmad and Verma

(2018), DSS can be complex to develop and maintain, requiring significant technical expertise and resources. User training is essential for effective utilization, and the quality of the system depends on the integration and reliability of data from various sources. These challenges can impact the system's effectiveness and accessibility for all potential users.

In the current study, DSS theory is applied through the use of the WEAP model as a decision support tool for simulating water supply and demand dynamics. The researcher will utilize DSS principles to integrate data, explore scenarios, and determine optimal water allocation strategies. By employing DSS theory, the researcher will enhance the study's capacity to provide actionable recommendations for sustainable water resource management and policy-making in the Upper Nzoia Catchment.

### **2.3 Conceptual Review**

This conceptual review synthesizes key principles of Integrated Water Resources Management (IWRM) and examines various Decision Support Systems (DSS) tools designed to address water allocation challenges. Focusing on the Kipkaren River within the Upper Nzoia Catchment, the review explores how these tools can be used to simulate and analyze water supply and demand dynamics. It evaluates the different DSS methodologies and their applications, aiming to provide insights into how these systems can improve decision-making and support sustainable water management practices in complex catchment environments.

#### **2.3.1 Integrated Water Resources Management**

Integrated Water Resources Management (IWRM) is widely recognized as a method that promotes the coordinated use and management of land, water, and related resources to enhance human social and economic well-being while ensuring the long-term

sustainability of essential ecosystems (Loucks *et al.*, 2017). This approach, endorsed by the Global Water Partnership (GWP), emphasizes the importance of considering both the ecological framework, which affects resource availability and quality, and human systems, which influence resource use, contamination, and socioeconomic priorities (Jain & Singh, 2023).

Despite its comprehensive nature, IWRM has faced criticism for being vague and overly speculative, particularly when applied to meso to macro-scale projects, where practical implementation can be challenging (Borgomeo *et al.*, 2018). The GWP has documented numerous successful applications of IWRM principles worldwide, illustrating how countries are adapting their water policies accordingly. For instance, Kenya is currently adopting IWRM-based reforms aimed at integrating key sectors and stakeholders in watershed management and water allocation (Phan, Bertone, & Stewart, 2021). However, the process often encounters delays and misunderstandings, particularly when management teams lack clarity on resource relationships and management strategies. To support effective decision-making at the catchment level, scientific methods and modeling tools—such as water balance models, groundwater flow models, and economic water consumption models—are increasingly utilized to simulate existing and potential scenarios of water resource growth and supply changes (Rad *et al.*, 2017; Ahmad & Verma, 2018). These tools help bridge the gap between theoretical concepts and practical implementation, aiding in the adaptation and optimization of water management strategies.

### **2.3.1.1 The Framework for Integrated Water Resources Planning and Management**

The technique widely accepted for managing sustainable water resources is integrated water management at the watershed level (Kumar & Bassi, 2021). This approach emphasizes considering the entire basin and all its components, including those that can both influence and be influenced by water resources. These components, which can be organized and analyzed using GIS database sets, are crucial for understanding the holistic impact of water management practices (Kirilov, Bournaski, & Iliev, 2022). One of the fundamental goals in water resource management is to maintain the health of aquatic and related terrestrial ecosystems while ensuring human well-being (Jeuland, Moffa, & Alfara, 2021). To achieve this, it is essential to assess and quantify the current state of the aquatic ecosystem, its impacts, and their evolution over time (Kolusu *et al.*, 2021). Tools such as GIS databases and integrated modeling approaches are instrumental in evaluating these dynamics, as they provide a comprehensive view of how water management strategies affect both the environment and human communities (Leal Cárdenas & Triana Pulido, 2022; Lakshmi, 2024).

### **2.3.2 Catchment–Based Decision Support Systems for Water allocation Modeling**

Several commercially available programs were evaluated for their suitability in studying various water catchment areas, taking into account their structure, required data inputs, and usage constraints. As detailed in Chadwick *et al.* (2021) and the Stockholm Environment Institute, the programs assessed include AQUATOOL, MODSIM, MULINO-DSS (MULTi-sectoral, Integrated and Operational Decision Support System), RIBASIM (River Basin Simulation Model), WBalMo (Water Balance Model), MIKE Basin, and WEAP System.

### 2.3.2.1 MODSIM

Almulla *et al.* (2022) describe MODSIM as a versatile Decision Support System (DSS) designed for simulating water distribution within river basins over specified time intervals. The system functions by resolving network flow optimization challenges sequentially, accounting for nonlinear factors such as evaporation, groundwater returns, and channel losses through a step-by-step evaluation-solution approach (Leong & Lai, 2017). MODSIM utilizes the Lagrangian relaxation algorithm, which facilitates a robust platform for customization and effective management of water resources across various operational areas. Its capability to integrate spatial arrangements of reservoir storage helps in balancing water distribution effectively (Chepyegon & Kamiya, 2018). Furthermore, MODSIM's integration with other systems, such as MODFLOW, allows for combined simulations of groundwater and surface water resources, enhancing its versatility (Fard & Sarjoughian, 2019).

In addition to its primary functionalities, MODSIM can operate within a stochastic optimization framework to generate optimal operational guidelines for dynamic programming (Fard & Sarjoughian, 2024). This capability addresses the challenge of minimum-cost water distribution by considering a comprehensive range of physical, hydrological, and institutional factors (Asghar *et al.*, 2019). Despite its strengths, the system's primary module requires a certain level of training to be utilized effectively, and the external modules present significant challenges without a solid background in modeling (Richards & Syallow, 2018). Overall, MODSIM's design and functionalities make it a powerful tool for water resource management, but it also demands a considerable level of expertise and integration with other models to achieve its full potential.

### 2.3.2.2 MIKE Basin

**MIKE BASIN** combines the functionalities of ArcView GIS with advanced hydrologic modeling to address issues related to water allocation, joint usage, reservoir operation, and water quality, aiming to improve basin-wide solutions (Aein & Alizadeh, 2021; Abou Slaymane & Soliman, 2022). The guiding principle of MIKE BASIN is to simplify modeling, turning it into an intuitive tool that delivers profound insights into water resource planning and management. Emphasis within MIKE BASIN is on effective visualization of simulation results across both time and space, which aids in fostering understanding and consensus (Abungba *et al.*, 2022). The tool uses a network model for hydrologic simulations, with nodes representing elements like confluences, reservoirs, diversions, or water users, and branches symbolizing specific stream sections. Its ArcView GIS interface is expandable, allowing for modifications to its network components (Psomasa *et al.*, 2016).

In technical terms, MIKE BASIN operates as a quasi-steady-state mass balance model, yet it supports river flow routing (Mayol, 2015). As noted by Aein and Alizadeh (2021), it models water quality outcomes based on pure advective transport, and it can simulate decay during transportation. Groundwater representations utilize inherent linear reservoir equations. Common use cases encompass water availability studies, combined management of surface and groundwater, infrastructure design, irrigation potential reviews, reservoir performance analysis, supply capacity projections, and determining wastewater treatment needs (Brown *et al.*, 2019; Abbas *et al.*, 2022). Furthermore, the model has been employed to assess demands across various sectors like domestic, industrial, agricultural, and others, as well as to analyze water quality, climate change impacts, regulatory matters, and water priorities (Agarwal *et al.*, 2019; Barría *et al.*, 2021).

Other tools related to MIKE include MIKE 11 for reservoir operations, MIKE FLOOD for flood surge management, MIKE21C predictions, and MIKE SHE for groundwater studies (Almulla *et al.*, 2022). Nevertheless, MIKE BASIN's overall efficacy remains underreported due to model constraints, such as the need for a complete discharge time series, data accuracy concerns, human capacity challenges, and unreliable spatial water withdrawal data (Abou Slaymane & Soliman, 2022). Additionally, the model necessitates time series data of naturalized flows.

### **2.3.2.3 AQUATOOL**

Asghar, Iqbal, Amin, and Ribbe (2019) define AQUATOOL as a versatile Decision Support System (DSS) tailored for both operational management and planning phases in intricate basins which include aquifers, demand hubs, and multiple reservoirs. Originated by the Universidad Politécnica de Valencia (UPV) in Valencia, Spain, the system has been programmed in various languages, such as Visual Basic, C++, and FORTRAN. The system has since evolved, now boasting simulation modules (SimWin) tailored for water resource and drought management, as well as optimization modules (SimRisk) for groundwater distribution.

In AQUATOOL, simultaneous management of simulation and surface water systems is possible. This facilitates the resolution of a steady flow network optimization for each month within a specific simulation period. Even though AQUATOOL operates on preset policies, users have the flexibility to select from an array of models for an authentic representation of groundwater. This can range from a basic reservoir model to a more intricate model of an unevenly shaped heterogeneous aquifer, as described by Ashrafi and Mahmoudi (2019) and Azmi Husain and Mohd Rhyme (2021).

#### **2.3.2.4 River Basin Simulation Model (RIBASIM)**

Fard & Sarjoughian, (2024) describes RIBASIM (River Basin Simulation Model) as a versatile modeling package designed to assess the behavior of river basins under various hydrological scenarios. It's a comprehensive and adaptable tool, connecting hydrological water inputs at different locations with specific water users within a basin. This model allows users to analyze a variety of strategies related to infrastructure, operations, and demand management. It has been employed in numerous projects across several countries. As Huber-Lee *et al.* (2020) point out, RIBASIM can be integrated with other software programs from Delft Hydraulics to conduct detailed water demand analyses, covering aspects like population and crop water needs, and to compare current and future demands at different locations. Heinzl *et al.* (2022) note that RIBASIM's architecture leverages an integrated approach, complemented by a user-friendly, visually appealing, and GIS-centric interface. Utilizing RIBASIM entails a systematic methodology to river basin planning and oversight.

#### **2.3.2.5 MULti-sectoral, Integrated and Operational DSS (MULINO – DSS)**

The MULINO-DSS was initiated by the European Union RTD project, with the goal of promoting sustainable water resource management at the catchment level, as mentioned by Moncada *et al.* (2020). Introduced in 2001, it aimed to assist water authorities in overseeing water resources, with a specific focus on enhancing decision-making quality. Furthermore, MULINO-DSS was designed to foster a holistic approach to river basin management. It merged socio-economic and environmental modeling techniques with GIS capabilities and multi-criteria decision aids. Using the Drivers-Pressures-States-Impacts-Responses (DPSIR) framework to structure decision-making challenges, this tool was

instrumental in implementing or adapting new European water directives in alignment with local regulations (Okyereh *et al.*, 2019).

### **2.3.2.6 Water Balance Model (WBalMo)**

The Water Balance Model, or WBalMo, is characterized by Tena *et al.* (2019) as an engaging simulation tool for managing river basins. Originating in Germany, WBalMo stochastically simulates natural phenomena like runoff and precipitation using a Monte-Carlo method. This is then harmonized with monthly water usage needs and alterations in reservoir storage (Poblete *et al.*, 2023). The WBalMo model has been instrumental in setting management directives for river basins, crafting reservoir systems along with their operational strategies, and conducting environmental assessments for developmental initiatives (Fanta *et al.*, 2022). Leveraging an ArcView interface, users can create or adapt a visual representation of the river basin, often referred to as a "system sketch," either from scratch or based on an existing digital stream network. This model data can then be adjusted according to different scenarios (Remilekun *et al.*, 2021). As the simulation progresses and captures pertinent system attributes, it can provide probability estimates concerning water shortages, upholding minimal runoff benchmarks, or reservoir water levels. The model supports simulations under both consistent and shifting conditions, such as those brought about by climate change (Tena *et al.*, 2019).

### **2.3.2.7 WEAP Model**

Tena *et al.* (2019) characterize WEAP as a versatile simulation tool that merges hydrological processes based on physical properties with demand management and infrastructure. This allows it to evaluate multiple scenarios, including changes in climate and human-induced stressors. Created by the Stockholm Environment Institute in Boston,

Massachusetts, WEAP's simulations consist of various scenarios with different time frames (Nordström, 2019). According to Muhammed *et al.* (2020), WEAP's GIS-supported, user-friendly drag & drop interface facilitates integrated water resource planning.

The foundational approach of WEAP involves simulating both water demands and supplies, allowing users to add custom variables and equations, all within a scenario management framework. As noted by Tena *et al.* (2019), WEAP can be integrated with spreadsheets and other models. Among its capabilities are sectoral demand analysis, water conservation assessments, water rights prioritization, groundwater and surface water simulations, reservoir management, hydropower evaluations, pollution tracking, and determining environmental needs. Using WEAP, users can explore different base scenarios to gauge the sensitivity of water resources to various demographic, technological, and climate/hydrological changes (Dehghani *et al.*, 2022). Similarly, to MODSIM, WEAP can interface with the MODFLOW model, which is a 3D groundwater model, allowing users to understand the interplay between groundwater changes and the broader system (Ghimire *et al.*, 2022). Additionally, by integrating with QUAL2E, WEAP can facilitate in-depth water quality analyses (Hatamkhani *et al.*, 2022). WEAP's groundwater module enables the simulation of water exchanges between rivers and aquifers. A core aspect of WEAP's water management analysis is examining different water demand setups, wherein these scenarios are applied to a linear programming allocation algorithm that assigns user-defined priorities to each demand and source (Mehraban *et al.*, 2024).

### **2.3.2 Catchment–Based Decision Support Systems for Water allocation Modeling**

From the provided descriptions, models like AQUATOOL, MODSIM, and WEAP operate based on optimization within a singular time frame, leveraging this for enhanced

simulations (Cepeda *et al.*, 2024). Conversely, MULINO-DSS, RIBASIM, WBalMo, and MIKE Basin are purely simulation-driven models that use traditional methodologies (Daniels *et al.*, 2020).

For MODSIM, water allocation considers physical, hydrological, and institutional elements, optimizing for the lowest cost flow (Muhammed *et al.*, 2020). WEAP, however, employs a linear program for each time step to address water allocation (Opoku Oti *et al.*, 2020). When employing purely simulation-based models like MULINO-DSS, RIBASIM, WBalMo, and MIKE Basin to intricate water systems, they tend to produce suboptimal performance metrics (Sadak *et al.*, 2024). Operational strategies in several models such as AQUATOOL, MULINO-DSS, RIBASIM, WBalMo, and MIKE Basin are set. Yet, in MODSIM and WEAP, they are determined by system states and hydrological conditions, allowing for customized rules without modifying the base codes (Brown *et al.*, 2019).

All seven reviewed models incorporate water quality modeling features. However, WEAP's water quality components and algorithms are comparatively simplistic (Saeed *et al.*, 2024). Both MODSIM and WEAP can be integrated with more advanced models, such as US-EPA, QUAL2E, and MODFLOW, to provide in-depth water quality analyses. However, MODFLOW entails a lengthy calibration phase, making it a challenging and time-consuming endeavor (Majedi *et al.*, 2020).

Summarizing, in the context of attributes like accuracy, usability, flexibility, and more, WEAP stands out as the preferred model for river basin analysis in the Yala catchment, especially for simulating water supply and demand allocation (Mehboob *et al.*, 2020). The discussed models have diverse applications, including catchment planning, water allocation, flow routing, and more. Nonetheless, no single model perfectly addresses all

these functionalities. Some models might excel in certain aspects compared to others. Literature indicates that the efficacy in managing hydrological processes can be enhanced by combining models like AQUATOOL with WEAP or MODSIM with WEAP, among other combinations (Musie *et al.*, 2021). Notably, WEAP can perform both centralized and distributed catchment hydrological simulations. Given adequate quality data, WEAP is notable for its adaptability in merging both hydrological and managerial models (Phung *et al.*, 2022).

In conclusion, based on recommendations by Droogers *et al.* (2014) and derived from various WEAP applications, this model is chosen for the current research. WEAP stands out due to its comprehensive approach to integrated water resources planning, its transparent structure allowing stakeholder engagement, and its versatile database. Additionally, its ability to calculate a plethora of parameters, handle various water system uses, and its user-friendly graphical interface, gives it an edge. Given its compatibility with other models, this study employed WEAP21 for the River Nzoia Catchment in Kenya, highlighting its superior features and user-friendliness (Fanta *et al.*, 2022).

## **2.4 Empirical Review**

This section reviews empirical studies that have applied WEAP to assess water availability and demand, simulate various management scenarios, and optimize water allocation. By analyzing these studies, the review provides insights into how WEAP can be effectively used to inform sustainable water management practices and policy decisions. The findings from this review are crucial for achieving the study's objectives, which include evaluating current water conditions, projecting future scenarios, and developing strategies for improved water resource management in the Upper Nzoia Catchment.

### 2.4.1 Water Availability and Demand

Abou Slaymane and Soliman (2022) investigated water balance and quality management in the Upper Litani Basin, using integrated models to assess the impacts of future climate and population growth on water resources. Their study underscores the importance of considering future scenarios in water management, especially in predicting changes in water quantity and quality. They noted limitations in the model's predictive capability for extreme events, which highlights the need for enhanced scenario planning and sensitivity analysis. This view is supported by Balderrama and Escobar (2023), who emphasize the significance of dealing with uncertainties in watershed modeling. Their research into the Bolivia Watch Program showcases the necessity of incorporating uncertainty into water management practices to better address the complexities of future water scenarios.

Abungba *et al.* (2022) explored how land use and climate change impact water resources in the Black Volta Basin. Their findings reveal that changes in land use and climate variables significantly affect water availability and demand. The study criticizes the spatial resolution of their models and the assumptions made regarding future scenarios, pointing to the importance of detailed and accurate modeling to capture local variability. This insight is crucial for improving predictions of water availability. Hadri *et al.* (2022) echo these concerns by demonstrating how integrated water management models can address water resource challenges under climate change, further highlighting the need for comprehensive modeling approaches to manage water resources effectively.

Abbas, Xuan, and Bailey (2022) utilized an integrated framework combining SWAT, MODFLOW, and WEAP to evaluate water resources under various climate scenarios. Their approach offers a holistic view by integrating both surface and groundwater models,

providing comprehensive insights into water availability and demand. However, they highlight challenges such as the complexity of integrating different models and the need for high-quality input data. Dehghanipour, Schoups, and Zahabiyoun (2019) similarly emphasize the importance of robust models in conjunctive water management. They stress the need for models that can handle interactions between surface and groundwater effectively, supporting the use of integrated Decision Support Systems (DSS) in assessing water resources.

#### **2.4.2 Scenario Analysis Using WEAP**

Vaziri and Ghahreman (2024) applied WEAP to predict potential evapotranspiration under climate change scenarios, demonstrating its effectiveness in analyzing how changing climate conditions can impact water demand. Their study highlights WEAP's strengths in incorporating climate projections but also critiques its reliance on general climate scenarios, suggesting that more localized data could enhance prediction accuracy. This aligns with Suaza Sierra *et al.* (2023), who integrate machine learning into distributed water budget models to improve water quality predictions. Their work illustrates the potential for advanced modeling techniques to address uncertainties and refine predictions, emphasizing the importance of incorporating cutting-edge approaches into scenario analyses.

Ougougdal *et al.* (2020) used WEAP to examine future water demand and supply under various climate and socio-economic scenarios in the Ourika Watershed, Morocco. Their research showcases WEAP's capabilities in modeling different scenarios to assess impacts on water resources. They note the model's utility in scenario analysis but highlight challenges such as the need for accurate future projections and the integration of socio-economic factors. Barría *et al.* (2021) address similar issues in their study of the Chilean

Aculeo Lake, where they investigate the causes of lake drying and the implications for water management under climate variability. This further underscores the need for comprehensive scenario analyses to capture a range of possible futures.

Asadi *et al.* (2024) employed WEAP to analyze hydrological alterations and environmental flows in a highly anthropized river basin. Their research demonstrates WEAP's role in assessing the impact of various management scenarios and policies on water resources. They critique the model's ability to fully capture complex socio-economic interactions and environmental changes. This insight is valuable as it highlights the need to consider diverse management scenarios and their broader implications for water resource planning. Reznik *et al.* (2022) similarly emphasize the importance of incorporating institutional and economic factors into modeling for better water management outcomes, suggesting a need for holistic approaches in scenario analyses.

### **2.4.3 Optimization of Water Allocation Using WEAP**

Salomón-Sirolesi and Farinós-Dasí (2019) explored water governance models for managing irrigation and land development in the Mendoza River Basin, Argentina, using WEAP. Their findings illustrate the model's capability in addressing water allocation conflicts and optimizing resource use. They critique the model's static nature and the practical challenges of implementing governance models, highlighting the need for adaptive strategies in water allocation. Limantara *et al.* (2024) provide additional insights into optimizing water allocation through performance index models, emphasizing the importance of decision support tools in improving water management outcomes.

Agarwal *et al.* (2019) used WEAP to optimize water supply and demand in the Ur River watershed, India. Their study demonstrates WEAP's effectiveness in balancing water

allocation among various users and sectors. They critique the model's limitations in handling dynamic water availability and stress the need for frequent recalibration to reflect real-time conditions. Hamlat *et al.* (2024) address similar issues in their study of water supply and demand balancing in Algeria, showcasing the challenges and strategies for improving model accuracy and reliability in semi-arid regions.

Wu, Alfonso, and Xinjun (2023) presented an integrated model for optimizing water resources in coastal areas by combining upstream streamflow regulation with local measures. Their study highlights how integrating various management strategies can enhance water allocation efficiency. They note challenges in aligning different regulatory frameworks and ensuring model compatibility. This approach is relevant as it suggests a multi-faceted strategy for optimizing water allocation, potentially integrating various DSS tools for a comprehensive solution. Hadri *et al.* (2022) also emphasize the importance of integrated approaches in water management, particularly under changing climatic conditions, further supporting the need for diverse strategies in water allocation.

#### **2.4.4 Recommendations for Sustainable Water Management**

Jeuland *et al.* (2021) examined water savings through infrastructure improvements and wastewater reuse in Jordan. Their study emphasizes the need for a holistic approach that incorporates both hydrological and socio-economic factors in water management. They critique the model's ability to capture all socio-economic variables and the need for detailed data. This research is relevant for developing practical and context-specific recommendations for sustainable water management. Dehghanipour *et al.* (2019) provide similar recommendations for conjunctive water management, stressing the importance of

integrating various strategies to achieve sustainability and manage water resources effectively.

FAO (2024) provided guidelines for using WEAP to calculate indicators related to water stress and sustainability. Their framework emphasizes integrating diverse data sources and management practices to achieve sustainable water use. They critique the challenges related to data accuracy and model limitations in predicting long-term sustainability. This resource is highly relevant for your study as it offers a structured approach to developing actionable recommendations for sustainable water management. Sadak, van de Giesen, and Abraham (2024) support this perspective by showcasing how integrated modeling approaches can enhance water, energy, and food system sustainability, demonstrating the value of comprehensive and integrated strategies.

Almulla *et al.* (2022) used participatory processes to analyze the agriculture-water-energy nexus in Morocco, highlighting the importance of stakeholder involvement in developing sustainable water management strategies. They discuss challenges in balancing diverse interests and integrating various sectors into management plans. This underscores the need for stakeholder engagement and consideration of multiple dimensions of water management in recommendations. Reznik *et al.* (2022) similarly highlight the importance of incorporating institutional factors into water management strategies to enhance their effectiveness and sustainability, emphasizing the role of governance and policy in achieving successful water resource management outcomes

## **2.5 Summary and Research Gaps**

The literature review revealed several gaps that need to be addressed. Therefore, this section provides a summary of reviewed literature, highlighting the selected research gaps that this research study aims to fill. These gaps are listed in Table 2.1.

**Table 2.1: Summary of Literature Review & Research Gaps**

<b>Author</b>	<b>Study Focus</b>	<b>Findings and Knowledge</b>	<b>Research Gaps</b>	<b>Focus of the Current Study</b>
Abbas, Xuan, & Bailey (2022)	Climate change impact on water resources using SWAT-MODFLOW-WEAP	Identified significant impacts of climate change on water availability and demand, using integrated modeling tools.	Need for better calibration and validation under diverse climate scenarios.	Assessed current water availability and demand in the Kipkaren River using WEAP.
Dehghanipour <i>et al.</i> (2019)	Conjunctive water management using WEAP-MODFLOW in Urmia Lake Basin	Effective in managing both surface and groundwater resources for sustainable development.	Limited focus on future climate and socio-economic changes.	Assessed current water availability and demand in the Kipkaren River, leveraging insights from conjunctive management approaches.
Ndayishimiye <i>et al.</i> (2022)	Effects of drought on hydroelectric power in Uganda	Analyzed how drought conditions impact power generation, emphasizing the need for improved water management.	Insufficient focus on comprehensive water allocation strategies and adaptive measures.	Used WEAP to assessed water availability and demand, considering potential impacts on power generation.
Agarwal <i>et al.</i> (2019)	Water supply-demand assessment using WEAP in the Ur River watershed	Demonstrated WEAP’s effectiveness in balancing water supply and demand for a specific watershed.	Limited application to larger or different types of watersheds.	Simulated implications of various scenarios using the WEAP model in the Upper Nzoia Catchment.
Hamlat <i>et al.</i> (2024)	Water supply and demand forecasting in a semi-arid region using WEAP	Highlighted challenges and strategies for balancing water supply and demand in arid regions.	Lack of focus on diverse climatic and socio-economic scenarios.	Simulated various scenarios using the WEAP model to address specific regional challenges.

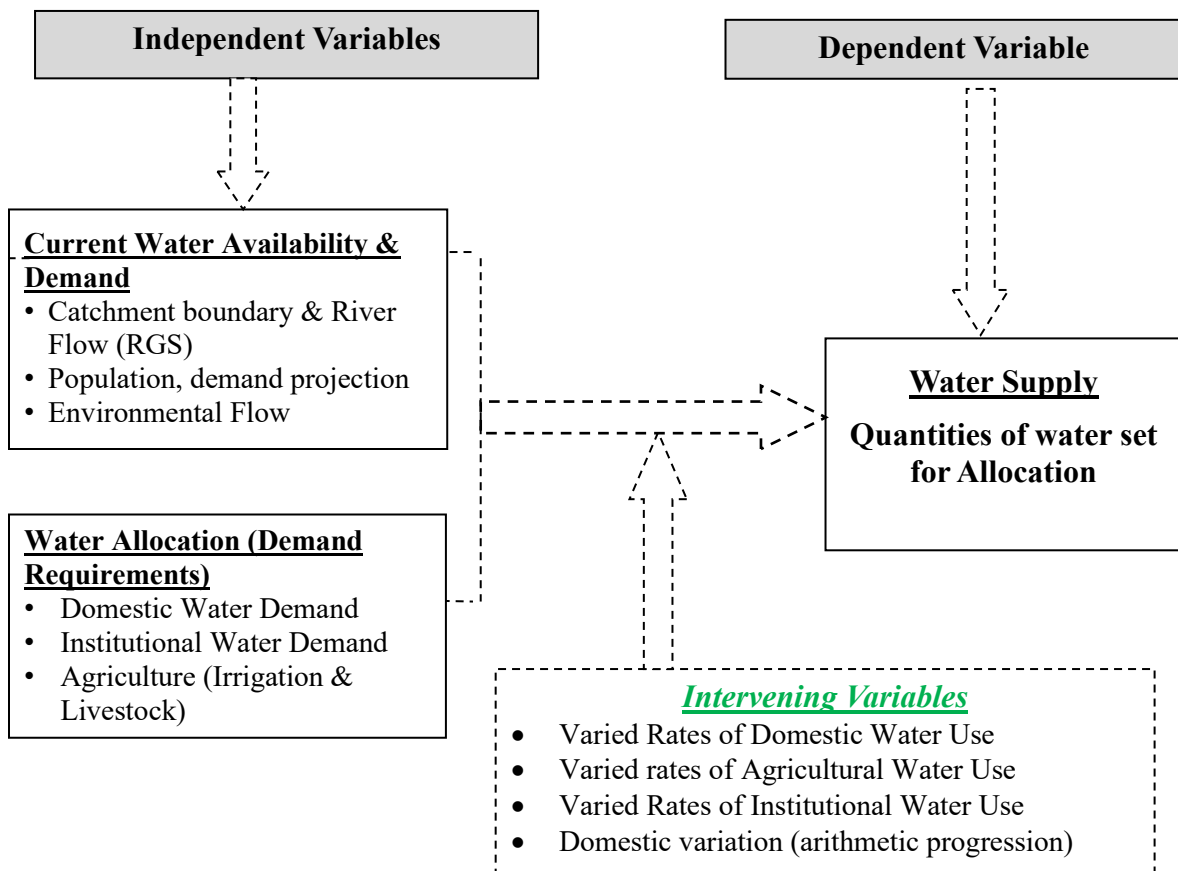
<b>Author</b>	<b>Study Focus</b>	<b>Findings and Knowledge</b>	<b>Research Gaps</b>	<b>Focus of the Current Study</b>
Suaza Sierra <i>et al.</i> (2023)	Integrating machine learning with water budget models for water quality predictions	Demonstrated the benefits of combining machine learning with traditional models for improved predictions.	Limited focus on integrating machine learning with specific DSS like WEAP.	Explored implications of various scenarios using WEAP, potentially incorporating advanced predictive techniques.
Vaziri & Ghahreman (2024)	Prediction of potential evapotranspiration using WEAP under climate change scenarios	Showed WEAP's capability in predicting evapotranspiration and its impacts on water resources.	Need for broader application to various climatic and socio-economic contexts.	Applied WEAP to simulate implications of different scenarios on water resources in the Upper Nzoia Catchment.
Cepeda <i>et al.</i> (2024)	Water security in an Andean basin using multi-scenario assessments	Provided insights into water security through integrated socio-hydrological models.	Limited focus on specific catchments and practical policy recommendations.	Recommend actionable strategies for sustainable water resource management and policy-making in the Upper Nzoia Catchment.
Asghar <i>et al.</i> (2019)	Integrated hydrological modeling in the Central Indus Basin using WEAP	Showed how WEAP can be used for water demand and supply assessment under socio-economic and climate scenarios.	Need for integration with other models for comprehensive water resource management.	Determined optimal water allocation within the catchment using the WEAP Model.
Hadri <i>et al.</i> (2022)	Integrated water management under climate change using WEAP	Demonstrated the application of WEAP in managing water resources in Mediterranean arid regions.	Need for application to different climatic zones and better integration with policy-making processes.	Determined optimal water allocation in the Upper Nzoia Catchment and test different scenarios using WEAP.

<b>Author</b>	<b>Study Focus</b>	<b>Findings and Knowledge</b>	<b>Research Gaps</b>	<b>Focus of the Current Study</b>
Reznik <i>et al.</i> (2022)	Economic efficiency of managed aquifer recharge in California	Highlighted the role of managed aquifer recharge in mitigating drought impacts on agriculture.	Need for more robust decision-support frameworks for water allocation and policy integration.	Simulated optimal water allocation strategies using WEAP to address efficiency and sustainability in the Upper Nzoia Catchment.
Leal Cárdenas & Triana Pulido (2022)	Flood risk mitigation in the upper Combeima River basin	Developed sustainable flood risk management strategies using integrated models.	Lack of detailed application to water demand and allocation aspects.	Recommended strategies for sustainable water management, considering flood risk and other factors.

*Source: Study Data (2024)*

## 2.6 Conceptual Framework

Mugenda and Mugenda (2006) defines conceptual framework as a conjunctured classification model that illustrates relationship between identified variables and how they would interact to answer the research questions or study hypotheses. The design of this research is explained by the conceptual framework (*Figure 3.1*), which has been developed as a summary of the attributes, processes and tools needed for its implementation. The framework illustrates the manner in which input data is collected then processed with the WEAP software to generate desired output. The independent variables are (i) distribution of available river water and (ii) the Scenarios. The first entail catchment boundary, river flow and environmental flow (Figure 2.1).



**Figure 2.1: Conceptual Framework**

Source: Researcher (2024); Okungu (2018)

## CHAPTER THREE

### RESEARCH METHODOLOGY

#### 3.1 Introduction

This chapter details the steps to achieve the study's goals. It begins with a description of the research area's specifics, including location and population trends. The development of research tools, including a prototype survey and sampling plan, are discussed. Data gathering methods, materials used, and data analysis processes are covered. The chapter mentions data types, participant attributes, and introduces the WEAP software programme. Model calibration, validation, scenario specifics, and study results are also outlined.

#### 3.2 Description of the Study Area

##### 3.2.1 Location

The research study was conducted on the Kipkaren River within the Upper Nzoia Catchment in Kenya, situated between latitudes 1°30'N and 0°05'S and longitudes 34°E and 35°45'E. Covering approximately 12,904 km<sup>2</sup>, this catchment includes key subcatchments such as the Nandi Hills, Cherangani Hills, and Mount Elgon, which are vital water sources for the region. The Kipkaren River, a major tributary of the Nzoia River, extends about 85 kilometers and is fed by important tributaries like the Sosiani River (Maloba *et al.*, 2016). It flows through a diverse landscape featuring agricultural areas, forests, and human settlements. Major towns in the catchment include Eldoret, Kitale, and Kapsabet, all connected by major roads such as the A104 and B2 highways.

The catchment's altitude ranges from approximately 1,500 meters to over 4,300 meters above sea level, with Mount Elgon being the highest point. The region experiences a bimodal

rainfall pattern, with annual precipitation between 1,200 mm and 2,000 mm. Temperatures vary by altitude, averaging between 14°C and 26°C. The soils in the catchment are mostly volcanic, with fertile loam and clay types supporting a variety of agricultural activities. Vegetation includes montane forests, grasslands, and cultivated lands, with significant forested areas in the highlands enhancing the region's water catchment capabilities. The river's flow volume fluctuates seasonally due to rainfall variations and is crucial to the hydrology of the Upper Nzoia Catchment, while also significantly benefiting the Lower Nzoia Catchment (Koskei *et al.*, 2024).

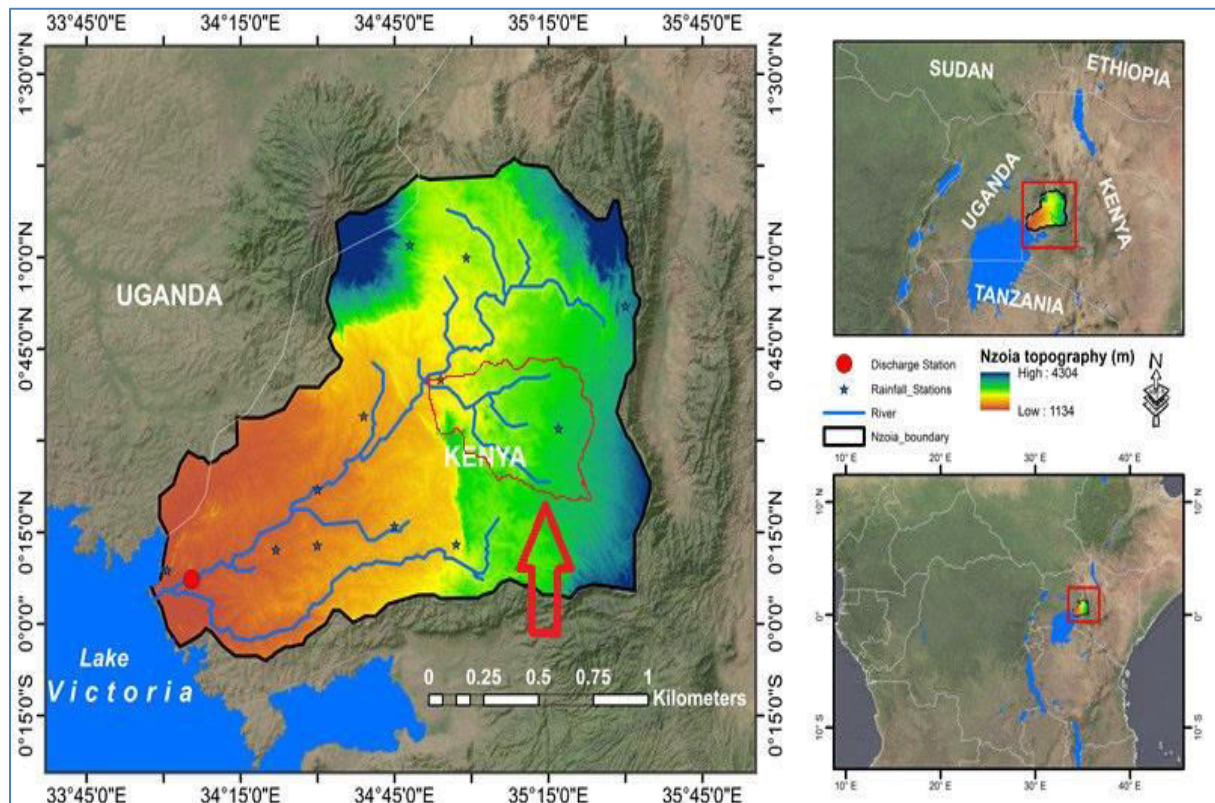


Figure 3.1a Map of Nzoia Catchment showing Kipkaren River  
 Source: Chepyegon & Kamiya, 2018).

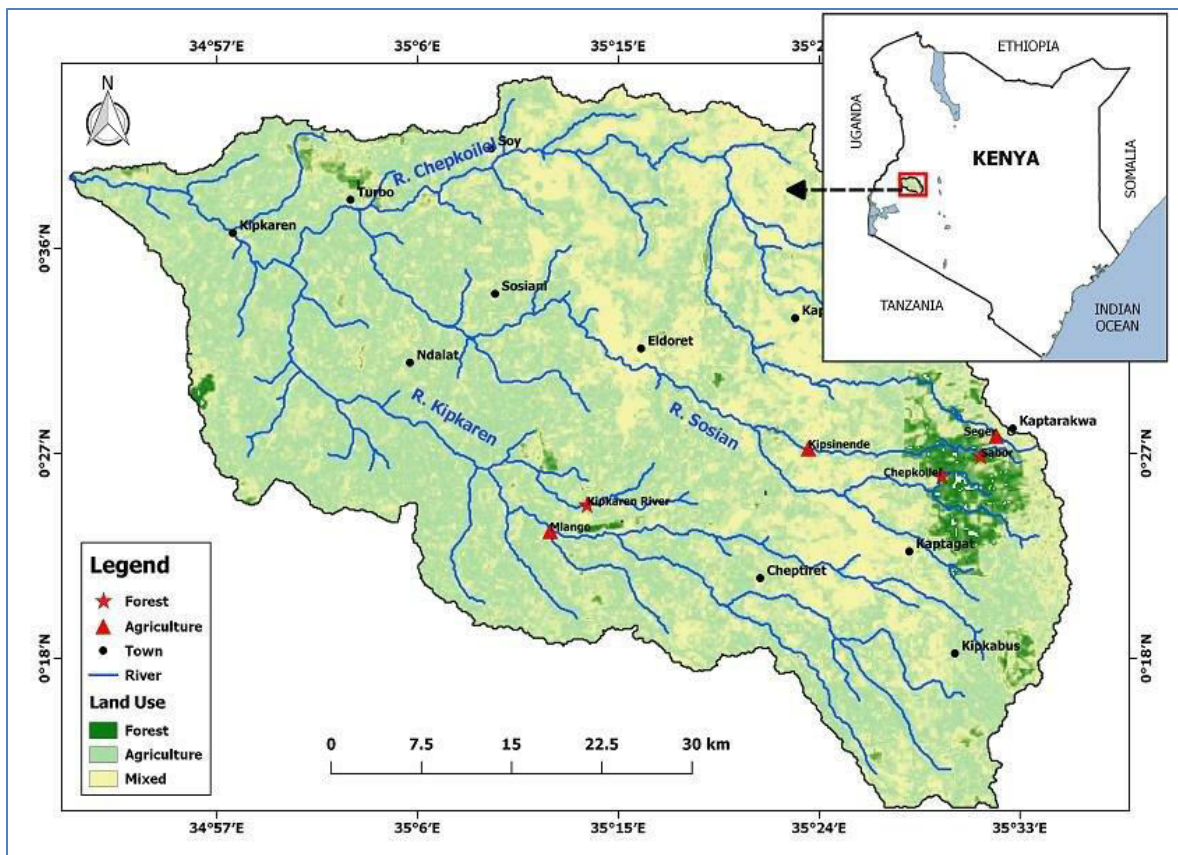


Figure 3.1b Map of Kipkaren River network  
 Source: QGIS Shapefiles – Western Kenya

### 3.2.2 Climate

The Kipkaren River, located within the Upper Nzoia Catchment, experiences a bimodal rainfall pattern characterized by two distinct rainy seasons each year. The long rains occur from March to May, while the short rains take place from October to December. This pattern is influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), which brings moist air and precipitation to the region. Annual rainfall in the area ranges from 1,200 mm to 2,000 mm, with variations influenced by altitude and local topography (Source: Chepyegon & Kamiya, 2018).

Temperature in the Kipkaren River varies significantly with altitude. Generally, temperatures range from 14°C to 26°C. Higher altitudes, such as those near Mount Elgon, experience

cooler temperatures due to elevation, while lower areas are warmer. The region has distinct wet and dry seasons: the wet seasons correspond to the bimodal rainfall pattern, while the dry seasons occur from June to September and January to February. These seasonal variations impact the flow volume of the Kipkaren River, with higher volumes during the rainy seasons and lower volumes during the dry periods.

### **3.2.3 Vegetation**

The Kipkaren River features diverse vegetation that reflects its varied landscape and climatic conditions. The area encompasses montane forests, grasslands, and cultivated lands. The highlands, particularly around Mount Elgon and the Cherangani Hills, are characterized by significant forest cover. These forests are crucial for enhancing the region's water catchment capabilities by maintaining soil moisture and reducing runoff. The diverse vegetation contributes to the ecological health of the region (Aura *et al.*, 2024).

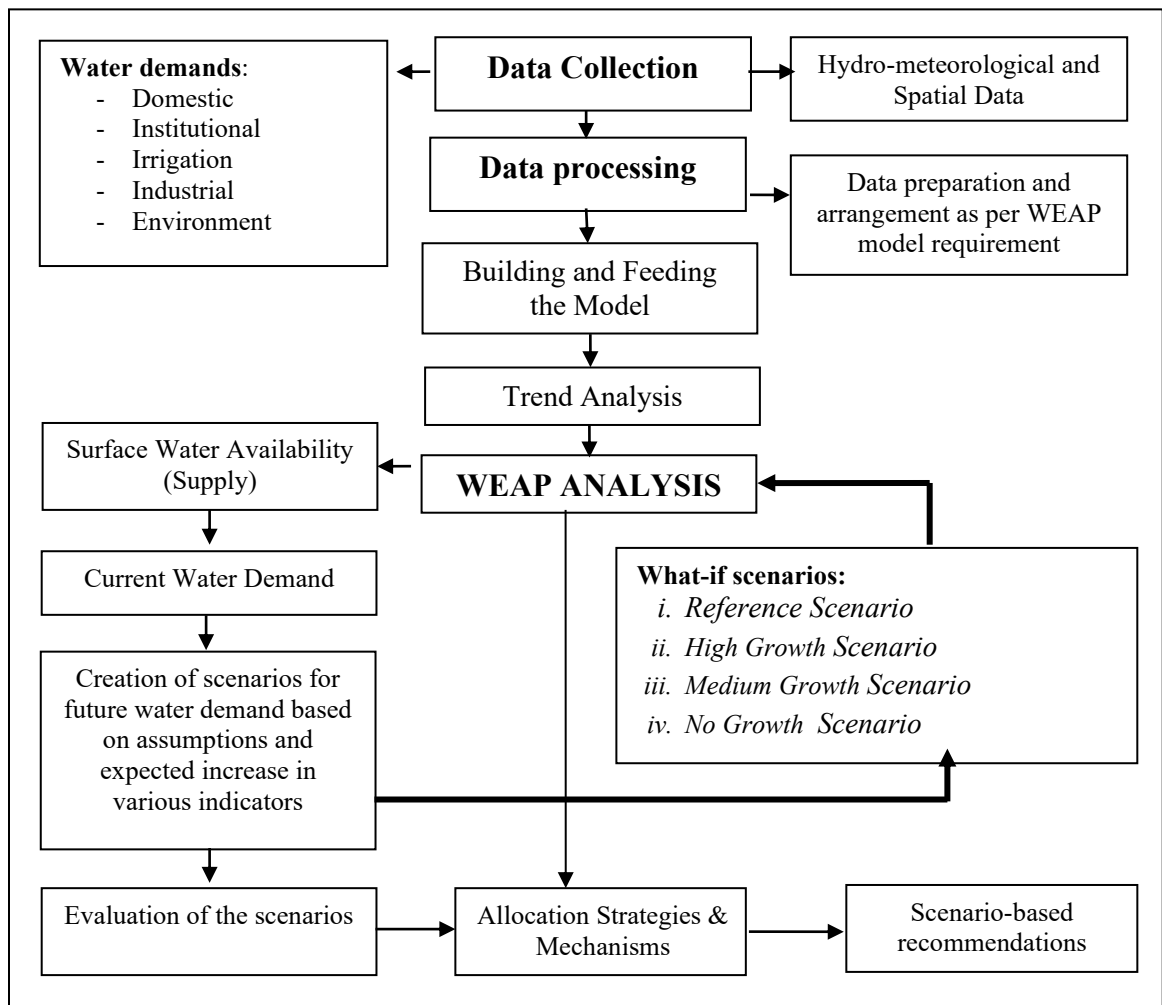
### **3.2.4 Soils**

The soils in the Kipkaren River are predominantly volcanic in origin, resulting in fertile loam and clay types. These fertile soils are ideal for agriculture, supporting the cultivation of a variety of crops, including maize, tea, coffee, and horticultural produce. Agriculture plays a key role in the local economy, and the rich soils contribute to high crop yields and food security for the region's inhabitants.

## **3.3 Research Design**

This research utilized a mixed-methods research design, integrating quantitative and qualitative approaches to simulate water supply and demand dynamics in the Kipkaren River within the Upper Nzoia Catchment (Maloba *et al.*, 2016). The design commenced with the collection of comprehensive data on hydrological conditions, water quality, and demand

across various sectors, including agriculture, domestic use, industry, and livestock. The WEAP model was employed to simulate different scenarios based on this data, assessing the impacts of changes in land use, climate, and population growth. This research was designed as illustrated in Figure 3.6.



**Figure 3.2: A flow chart of research design**

Source: Researcher (2024)

The water availability was assessed based on the water stream discharge to the Kipkaren River Area. Other factors such as rain-fed supplies and other aspects affecting supply were taken care of using variations in Annual Activity Levels, Annual Water Use Rate, Monthly Variations, Consumption Rates and Losses and Reuse of stream water.

### **3.4 Data Collection**

The data collection procedure for this research focused on thoroughly understanding water dynamics in the Kipkaren River within the Upper Nzoia Catchment. This involved gathering historical and current hydrological data, including river flow and rainfall measurements, as well as water quality assessments through sampling and laboratory analysis. Additionally, detailed information on water demand was collected from agricultural, domestic, industrial, and livestock sectors through surveys and interviews. This comprehensive approach ensured a robust dataset for accurate modeling and simulation of water supply and demand dynamics using the WEAP model.

#### **3.4.1 Assessing Current Water Availability and Demand**

##### *3.4.1.1 Hydrological Data Collection*

Historical flow data were collected from gauging stations along the Kipkaren River, including daily or monthly discharge records for the past 10–20 years. Key stations used in the analysis include 1EE01 – Kipkaren at Kipkaren Trading Centre, 1EE02 – Kipkaren at Moi’s Bridge, 1EE03 – Kipkaren upstream of Turbo, 1EE04 – Kipkaren at Kapsaret, and 1EE05 – Kipkaren at Chekalini. These stations fall under the monitoring network of the Water Resources Authority (WRA) and provide essential streamflow records for the calibration and validation of the hydrological model used in this study. Historical and current rainfall data were obtained from local meteorological stations within the catchment.

##### *3.4.1.2 Water Demand Data*

**Agricultural Use:** Data on water usage for irrigation, including crop types, irrigation methods, and seasonal water requirements, were gathered through surveys and interviews with local farmers.

**Domestic Use:** Data on domestic water consumption rates, including daily or monthly water use per household, sources of water (e.g., piped water, wells, surface water), and seasonal variations, were collected through household surveys, interviews, and utility records.

**Industrial Use:** Information on water consumption rates from industries and commercial establishments was obtained from utility companies, local government records, and direct surveys.

**Livestock Use:** Data on the water needs for livestock, including types of animals, their population, and their daily or seasonal water consumption, were collected through surveys and interviews with local farmers and livestock owners. Information on sources of water for livestock, such as rivers, ponds, or dedicated water troughs, was also gathered.

Environmental flow requirements were considered using reserve flow analysis methodologies, applying monthly flow benchmarks as defined under the Environmental Management and Coordination (Water Quality) Regulations, 2006.

These datasets were integrated into the WEAP model to inform catchment-scale simulation of water balance, allocation efficiency, and stress responses under varying demand scenarios. The triangulation of empirical surveys, secondary data, and model-ready inputs ensured data robustness and consistency with national planning thresholds.

### **3.4.2 Simulating Implications of Various Scenarios Using the WEAP Model**

#### *3.4.2.1 Model Setup and Calibration*

**Data Preparation:** The collected hydrological, water quality, and demand data were compiled into a format compatible with the WEAP model.

**Calibration:** The WEAP model was calibrated using historical data to ensure that simulated outputs accurately reflected past observations of water availability and demand.

#### *3.4.2.2 Scenario Development*

**Scenario Identification:** To assess the future dynamics of water supply and demand in the Kipkaren River Sub-Catchment, four exploratory scenarios were developed using the WEAP model. These scenarios were informed by Kenya’s long-term development frameworks, land use policies, and climate projections. Each scenario was designed to simulate plausible socioeconomic and environmental futures and assess the corresponding water system responses.

**Reference Scenario:** The Reference Scenario represents a “business-as-usual” trajectory, assuming continuation of existing trends in demographic growth, land use, and climate without significant policy changes or technological innovations. This scenario aligns with the base case outlined in the National Water Master Plan (NWMP) 2030 and reflects the water sector’s performance under current service delivery structures and development inertia. It provides a benchmark for evaluating the relative impacts of more proactive or extreme futures and helps assess how the current system might evolve in the absence of new interventions.

**High Growth Scenario:** This scenario envisions rapid economic and demographic expansion, with significant urbanization and agricultural intensification in the Kipkaren Sub-Catchment. It mirrors the ambitions of Kenya Vision 2030, particularly under the economic pillar, which prioritizes industrial growth and infrastructure expansion. Increased water demand is projected due to population influx into urban centers like Eldoret and growth in irrigation schemes and industrial water use. Land use change in this scenario includes conversion of forests and grasslands into urban or cultivated areas, and rising water stress is simulated under moderate to severe climate variability. This scenario reflects the

need to test infrastructure resilience and governance capacity in managing demand surges and declining water quality.

**Medium Growth Scenario:** The Medium Growth Scenario captures a more balanced trajectory that incorporates moderate socioeconomic development, environmental stewardship, and partial policy implementation. It is informed by the Fourth Medium-Term Plan (MTP IV, 2023–2027) and County Integrated Development Plans (CIDPs), which propose phased infrastructure expansion, agricultural modernization, and enhanced ecosystem protection. Climate projections under this scenario assume modest increases in temperature and variability in precipitation patterns, while land use change is guided by existing county-level spatial planning frameworks. This scenario serves as a plausible and policy-aligned middle ground between the more extreme Reference and High Growth cases.

**No Growth Scenario:** This scenario models a future characterized by stagnation in socioeconomic development due to limited investment, policy inaction, or external shocks. It assumes negligible changes in land use, population growth, and economic activity. While unrealistic as a long-term outcome, this “no-growth” trajectory provides a counterfactual baseline that helps isolate the role of active development planning. It is useful for highlighting the consequences of failing to implement national and county policy frameworks and underscores the risks of under-investment in water infrastructure and service delivery. Moreover, it serves as a stress-test to evaluate the system's minimum performance threshold under near-static conditions.

**Data Integration:** For each scenario, thematic data were integrated into the WEAP model to simulate differentiated futures. This included spatial layers of projected land use from county GIS platforms, climate forecasts from regional and IPCC datasets (e.g., RCP 4.5 and RCP 8.5 pathways), and demographic and sectoral demand projections derived from Kenya National Bureau of Statistics (KNBS) and County Development Profiles. This enabled dynamic representation of rainfall variability, temperature shifts, and evolving water demand across domestic, agricultural, and environmental sectors within the sub-catchment.

### **3.4.3 Determining Optimal Water Allocation**

**Model Simulation:** The WEAP model was run under different scenarios to simulate water allocation outcomes. The results were analyzed to determine the effectiveness of various allocation strategies.

**Optimization:** The WEAP model's optimization tools were utilized to identify optimal water allocation strategies that balanced supply and demand across the catchment.

## **3.5 Data Analysis**

### **3.5.1 Model Development**

**Definition of the Study Area and Time Frame:** The study area was precisely defined as the Kipkaren River within the Upper Nzoia Catchment, encompassing its tributaries and associated water user sectors. The time frame for the analysis included historical data spanning the past 10-20 years and projected scenarios extending into the future, covering anticipated changes in land use, climate, and population growth.

**Creation of the Current Accounts:** Current accounts were established by integrating collected hydrological, water quality, and demand data into the WEAP model. This involved inputting historical flow measurements, water quality parameters, and detailed water use

information from agricultural, domestic, industrial, and livestock sectors. The current accounts served as the baseline for evaluating water availability and demand under present conditions.

**Creation of Scenarios:** Various scenarios were developed to simulate potential future conditions. These scenarios included changes in land use patterns, climate variability, population growth, and policy interventions. Each scenario was designed to explore different impacts on water supply and demand, allowing for a comprehensive assessment of potential future states.

**Evaluation of the Scenarios:** The scenarios were evaluated using the WEAP model to assess their impacts on water availability and demand. This involved running simulations to analyze how each scenario would affect water resources, including changes in flow rates, water quality, and allocation needs. The results were compared against current accounts to identify significant deviations and potential issues.

### **3.5.2 The WEAP Programme Platforms**

**WEAP Schematic:** The WEAP schematic was developed to visually represent the water system within the catchment, including key components such as rivers, reservoirs, demand sites, and water management infrastructure. This schematic provided a framework for understanding the interactions between different elements of the water system.

**Demand Sites:** Demand sites were identified and categorized based on their water use characteristics. These included agricultural fields, domestic water supply points, industrial facilities, and livestock watering locations. Each demand site was mapped within the WEAP model to reflect its specific water requirements and consumption patterns.

**Annual Activity Levels:** Annual activity levels for each demand site were established by analyzing historical data on water use and operational patterns. This data helped to define the typical annual demand for water at each site, including variations due to seasonal changes and operational cycles.

**Annual Water Use Rate:** The annual water use rate was calculated for each demand site, reflecting the total volume of water consumed over a year. This rate was derived from historical water use data and used to inform the WEAP model of the baseline consumption levels for each sector.

**Monthly Variation:** Monthly variation in water use was incorporated to account for seasonal fluctuations in demand. This involved analyzing historical data to identify patterns of water use throughout the year, which were then input into the WEAP model to simulate monthly changes in demand.

**Demand Sites Schematic Development:** A detailed schematic of demand sites was created to illustrate the spatial distribution and characteristics of water users within the catchment. This schematic facilitated the visualization of water demand and allocation needs across different sectors and locations.

**Priorities for Water Allocation:** Priorities for water allocation were established based on stakeholder input and predefined criteria. These priorities guided the allocation of water resources under various scenarios, ensuring that critical needs were met while balancing competing demands.

**Scenario Analysis:** The scenario analysis involved running simulations in the WEAP model to evaluate the impacts of each scenario on water supply and demand. The results were analyzed to determine how different scenarios would affect water availability, quality, and

allocation. This analysis provided insights into potential challenges and opportunities for managing water resources sustainably in the future.

### **3.6 Model Calibration and Validation**

#### **3.6.1 Calibration of the WEAP Model**

The primary objective of model calibration was to ensure that the WEAP model accurately reflects the observed water dynamics in the Kipkaren River catchment. Calibration involved adjusting model parameters to match historical data on river flow, water quality, and demand.

##### *3.6.1.1 Calibration Process:*

**Data Integration:** Historical hydrological data, including river flow measurements and rainfall records, were integrated into the WEAP model. This included setting up the model with actual past conditions to simulate historical water availability and usage.

**Parameter Adjustment:** Model parameters related to flow rates, water quality, and demand were adjusted iteratively. This included tuning parameters such as runoff coefficients, infiltration rates, and water demand factors to align simulated outputs with observed data.

**Historical Data Comparison:** Simulated results were compared with historical data for river discharge, water quality metrics, and demand patterns. Discrepancies between observed and simulated values were identified, and model parameters were further refined to minimize these differences.

**Sensitivity Analysis:** A sensitivity analysis was conducted to determine how changes in model parameters affected the outcomes. This helped identify which parameters had the most significant impact on model accuracy and guided further adjustments.

**Calibration Metrics:** The effectiveness of calibration was evaluated using statistical metrics such as Nash-Sutcliffe Efficiency (NSE), Mean Absolute Error (MAE), and Root Mean

Square Error (RMSE). These metrics quantified the degree of fit between observed and simulated data, ensuring that the model provided a reliable representation of the water system.

### **3.6.2 Validation of the WEAP Model**

**Validation Objectives:** Validation aimed to verify the accuracy and robustness of the WEAP model by comparing simulated outputs with independent datasets not used during calibration. This step was crucial to confirm the model's predictive capabilities and ensure its reliability for future scenarios.

#### *3.6.2.1 Validation Process:*

**Independent Data Collection:** Additional data sets, including recent hydrological records and water quality measurements not used during the calibration phase, were collected. These datasets served as benchmarks for validating the model's performance.

**Simulation of Validation Period:** The WEAP model was run using the calibrated parameters and independent data from a separate time period to simulate water dynamics. The model's predictions were compared against the independent datasets.

**Performance Evaluation:** Validation performance was assessed using the same metrics employed in calibration, such as NSE, MAE, and RMSE. Consistency between simulated results and independent observations indicated successful validation.

**Model Robustness Testing:** The model's robustness was tested by applying it to different scenarios and evaluating its stability and accuracy across varying conditions. This ensured that the model could handle a range of inputs and scenarios reliably.

**Validation Results:** The results of the validation process demonstrated how well the WEAP model could predict water dynamics and validate its performance. Positive validation results supported the model’s use for scenario analysis and decision-making.

### 3.6.3 Model Performance Metrics

Authors such as Okungu, Adeyemo and Otieno (2017) and Agarwal (2019), have relied on calibration and validation metrics with recommended mathematical expressions to conduct calibration and validation processes in WEAP.

In this study, model performance was rigorously evaluated using several key statistical metrics during the calibration phase. The Nash-Sutcliffe Efficiency (NSE) was used to assess how well the WEAP model's simulations matched observed data, with values approaching 1 indicating a good fit between simulated and actual water dynamics. Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were also calculated to quantify the average deviations and squared differences between observed and simulated values, respectively. These metrics provided insights into the model's precision and accuracy in predicting river flow and water quality.

During validation, these performance metrics were recalculated using independent datasets not involved in the calibration phase. This process tested the model’s robustness and its ability to generalize to new data. Consistency in the NSE, MAE, and RMSE across different time periods and scenarios was assessed to confirm the reliability of the model. The evaluation ensured that the WEAP model maintained accurate predictions and remained a dependable tool for analyzing future water dynamics.

The mathematical expressions to compute the parameters mentioned above are:

Mean Absolute Error (MAE).....(i)

$$MAE = \frac{1}{N} \sum_{i=1}^N |Q_{o_i} - Q_{s_i}|$$

Root Mean Square Error (RMSE) .....(ii)

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (Q_{o_i} - Q_{s_i})^2}{N}}$$

*NB: The mean absolute error (MAE) and root mean square error (RMSE) are used to measure the deviation between the model outputs and the observed flows. Values tend to be zero for perfect agreement between observed and simulated values*

Error in Volume (VE in %).....(iii)

$$VE = \frac{(V_o - V_s)}{V_o} \times 100$$

Nash-Sutcliffe Coefficient(R) .....(iv)

$$E = 1.0 - \frac{\sum_{i=1}^N (Q_{o_i} - Q_{s_i})^2}{\sum_{i=1}^N (Q_{o_i} - \bar{Q})^2}$$

Index of Agreement (IA) .....(v)

$$IA = 1.0 - \frac{\sum_{i=1}^N (Q_{o_i} - Q_{s_i})^2}{\sum_{i=1}^N \left( \left| Q_{s_i} - \bar{Q} \right| + \left| Q_{o_i} - \bar{Q} \right| \right)^2}$$

*The Index of Agreement = 1 indicates the best (perfect) performance of the model.*

Where:

$Q_{oi}$  is the observed streamflow at time ( m<sup>3</sup>/s)

$Q_{si}$  is the simulated streamflow at time ( m<sup>3</sup>/s )

$V_o$  is the observed streamflow volume (million m<sup>3</sup>/month)

$V_o$  is the simulated streamflow volume (million m<sup>3</sup>/month)

$Q$  is the average streamflow (m<sup>3</sup>/s )

### **3.6.4 Scenario Analysis**

#### **Sensitivity Analysis:**

Scenario analysis included a detailed sensitivity analysis to explore how variations in model parameters affected the simulation outcomes. Parameters such as runoff coefficients and infiltration rates were adjusted to determine their impact on the model's predictions. This analysis identified the most influential factors on water dynamics, providing insights into which parameters needed careful consideration for accurate simulations.

#### **Scenario Comparisons:**

Statistical tests were employed to compare results across different scenarios, examining the effects of varying land use, climate conditions, and water management strategies. By analyzing these comparisons, the study assessed how different scenarios influenced water supply and demand, allowing for an evaluation of the effectiveness of various water management strategies. This comprehensive analysis informed the development of robust recommendations for sustainable water resource management.

### **3.7 Ethical Considerations**

After obtaining a clearance letter from Masinde Muliro University of Science and Technology Research Ethics Committee, convened by the Directorate of Postgraduate Studies, and acquiring a research permit from the National Council of Science, Technology, and Innovation, the researcher commenced field data collection. A crucial step was obtaining a WEAP (Water Evaluation and Planning) license from the Stockholm Environment

Institute, which facilitated the simulation aspects of the study. Official requests were also sent to the Kitale Regional Office of Water Resources Authority, the Offices of Meteorological Departments, the County Government of Kakamega, and relevant water facilities institutions to ensure comprehensive data access and cooperation.

Ethical considerations were integral to the research process. Informed consent and transparency were prioritized, ensuring all stakeholders, including local communities and water authorities, were fully aware of the research objectives and methodologies. Data privacy was strictly maintained, with anonymization and secure storage of personal and location-specific information. The study adhered to recommended methodologies and approved standards, ensuring that simulation scenarios and recommendations were developed with a focus on sustainability and environmental impact. Consultation with environmental experts was conducted to mitigate potential negative effects.

Equity and fairness were central to the research approach, aiming to address disparities in water access and ensure that recommendations did not disproportionately affect vulnerable groups. Community engagement was emphasized, involving local communities to ensure that strategies were practical and culturally appropriate, providing tangible benefits such as improved water infrastructure. Compliance with ethical guidelines and regulatory requirements was maintained throughout, ensuring responsible conduct and positive contributions to water resource management in the Upper Nzoia Catchment.

## **CHAPTER FOUR**

### **RESULTS AND DISCUSSIONS**

#### **4.1 Introduction**

This chapter addresses the research questions from Chapter One by analyzing data from 1970 to 2015 and validating it using WEAP software. It incorporates current data from 2019 to simulate water demand for the period 2020-2050 across various scenarios. The first section answers the question regarding the spatial and temporal distribution of stream and river water resources, detailing calibration, validation, surface water potential, annual discharge, and summarizing water supply and distribution in the Kipkaren River. The second section examines how past and current scenarios influence future water demand in the River, providing a detailed simulation of water supply and demand for 2019-2050 through scenario analysis. Finally, the third section focuses on the quantities of water that can be allocated for different uses, discussing allocations for domestic, agricultural, and industrial categories during the same period while interpreting the necessary supply requirements.

#### **4.2 Calibration and Validation Results**

In this section, simulated results for naturalized flows at the control (gauging) station (ICE01) are compared to observed values from the WEAP model. The comparison reveals that the WEAP model effectively captures the hydrological dynamics of the Kipkaren River, as demonstrated in the calibration and validation processes detailed below.

The demand sites in this study include Kipkaren, Lumakanda, Turbo, and various irrigation farms, each representing key areas where water is utilized. The demand is categorized into four main sectors: commercial, irrigation, domestic, and institutional. This categorization provides a comprehensive understanding of water requirements across different user groups,

facilitating more effective water resource management and allocation strategies tailored to the specific needs of each sector within these demand sites. Figure 4.1 illustrate the demand WEAP-modelled sites:

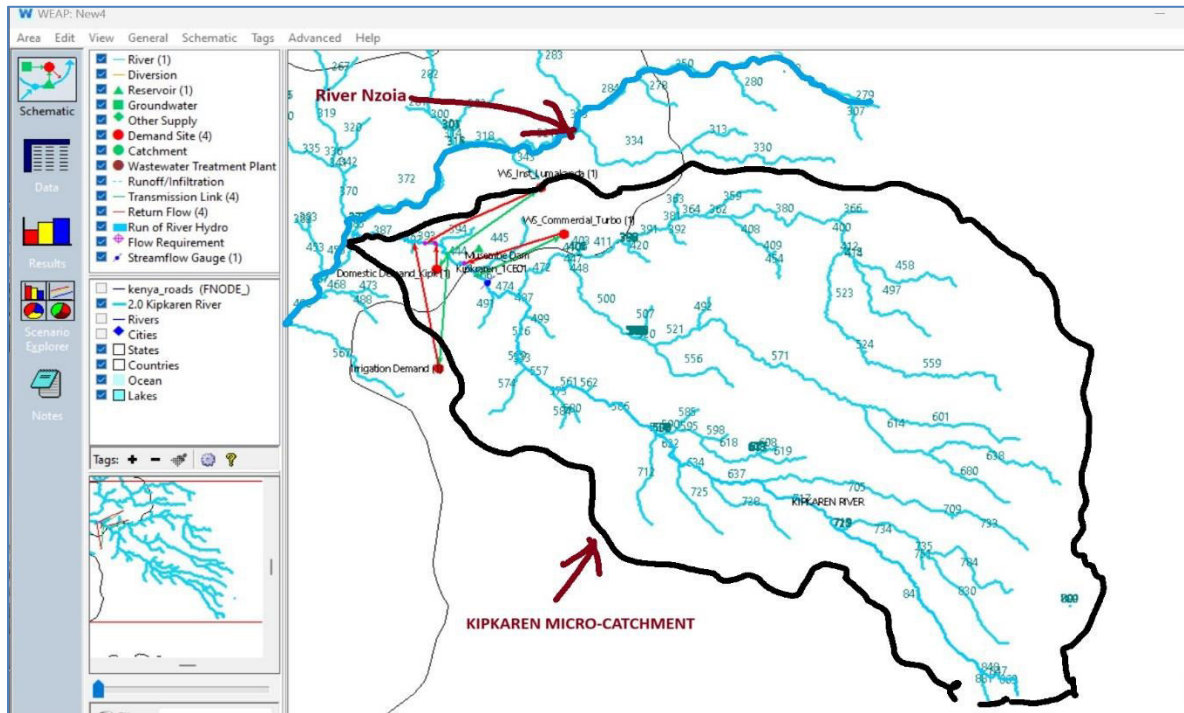


Figure 4.1: WEAP-modelled schematic with demand sites of Kipkaren River  
Source: Researcher (2024)

#### 4.2.1 Calibration results

Monthly simulated and observed streamflow data for the calibration period (1990–2000) at the ICE01 control station are presented in Figure 4.1. This figure compares simulated values (orange line) against observed streamflow records (blue dashed line), providing a visual assessment of the WEAP model’s performance in capturing hydrological behavior across seasonal cycles. The figure demonstrates the model’s ability to approximate both the magnitude and timing of peak and base flows within the Kipkaren Sub-Catchment.

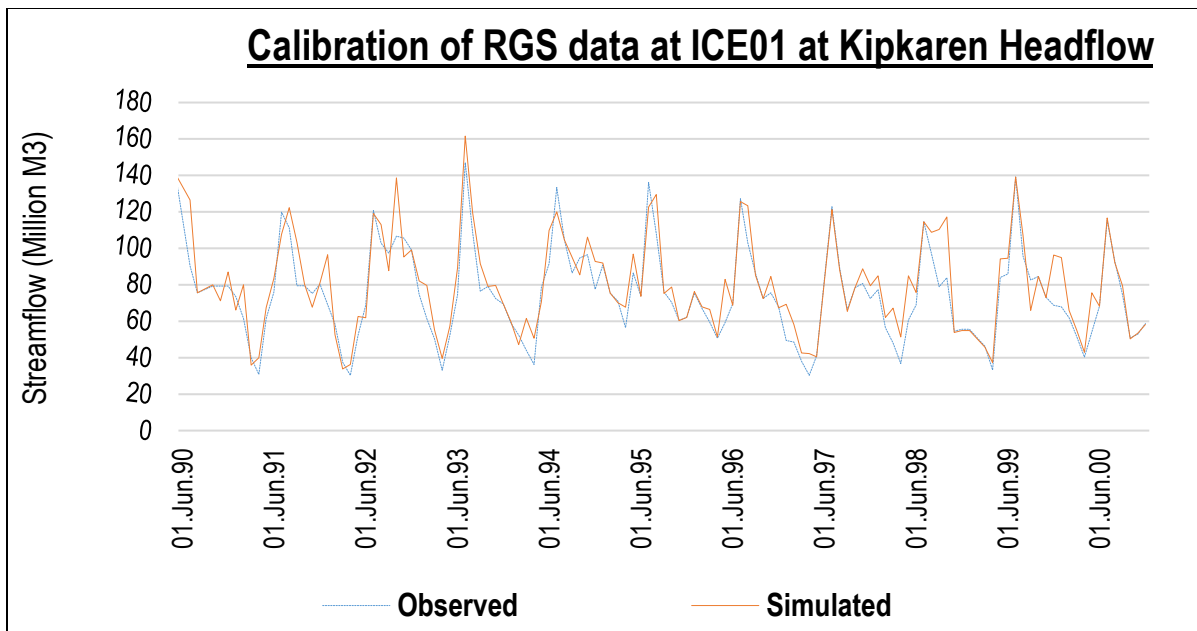


Figure 4.2: Calibration results showing observed and simulated stream-flows at selected stations in Kipkaren micro- catchment

Figure 4.2 illustrates the model’s calibration performance using scatter plots of observed versus simulated values across selected stations. This figure highlights the strength of correlation and model efficiency. Quantitative performance metrics—including a Nash–Sutcliffe Efficiency (NSE) of 0.74 and an  $R^2$  value of 0.78 - indicate satisfactory model behavior, with moderate discrepancies during high-flow months likely due to input data uncertainty and routing assumptions.

The figure presents tabulated calibration statistics alongside hydrographs and scatterplots, offering a triangulated view of model reliability. The observed trends suggest minor underestimations during peak rainfall periods and slight overestimations during dry seasons. These discrepancies imply the need for cautious interpretation during stress scenarios.

Implications for demand management: The seasonal flow trends revealed by the calibration exercise underscore the importance of timing in water allocation. Peak flows typically occur between April and August, suggesting that storage infrastructure and demand scheduling

should be optimized around these periods. Conversely, observed low flows from December through February highlight potential stress windows, where demand–supply mismatches may necessitate rationing or prioritization strategies under future development scenarios.

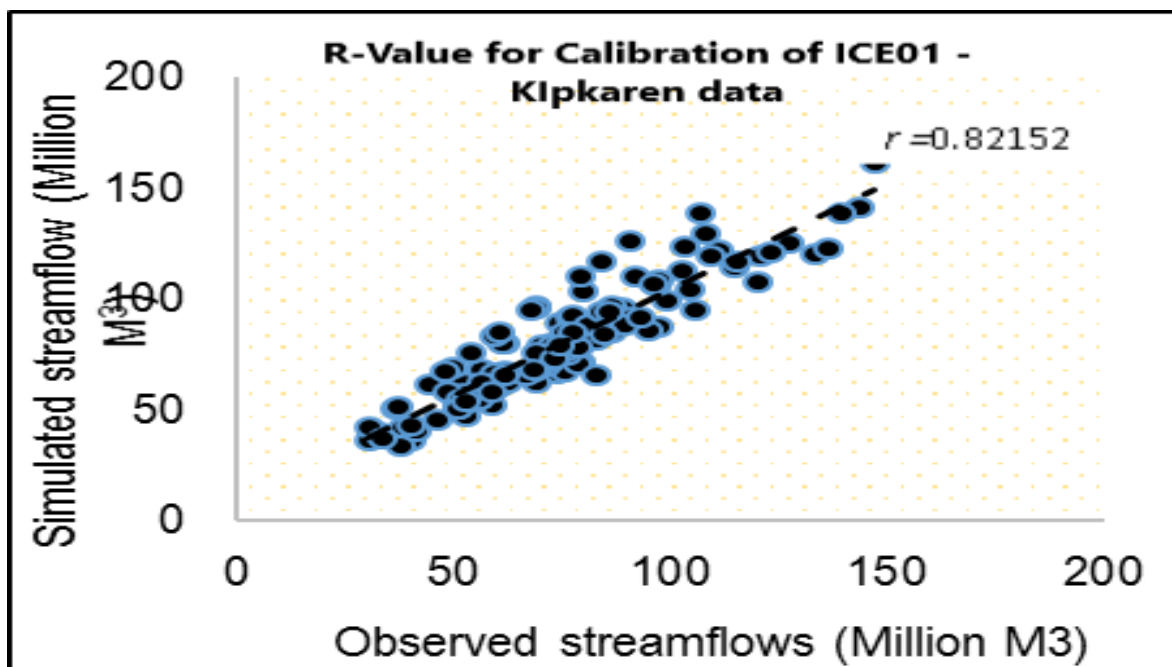


Figure 4.3: Calibration results showing Relationship between monthly observed and simulated streamflow in control stations of Kipkaren micro- catchment .

The results presented in Figure 4.3 highlight the calibration outcomes for the WEAP model at the Kipkaren gauging station (ICE01) for the period from 1990 to 2000. This table includes various fit statistics that evaluate the model's performance in simulating streamflow data. Key metrics such as mean observed and simulated flows, standard deviations, and error measurements are provided to assess the model's accuracy and reliability. As noted by Okungu *et al.* (2017), the inclusion of statistical indicators like the Nash-Sutcliffe coefficient and the index of agreement is essential to gauge the model's ability to replicate observed

hydrological dynamics. Such analysis is crucial for understanding the model's effectiveness in water resource management within the Kipkaren River.

Moreover, as highlighted by Poblete *et al.* (2023), employing robust decision-making methods in water resource modeling can enhance the reliability of predictions, especially in complex environments. The importance of integrating modern optimization techniques in water resources planning, as discussed by Tayfur (2017), also supports the relevance of the WEAP model in facilitating effective water management strategies. Collectively, these insights reinforce the need for rigorous model evaluation to ensure sustainability in water resource management.

**Table 4.1:** Fit Statistics of Simulated data by WEAP and Observed Stream Flow data for calibration

<b>Fit Statistic</b>	<b>ICE01 at Kipkaren RGS</b>
<b>Mean Observed Flow (m<sup>3</sup>/s)</b>	69.118
<b>Mean Simulated Flow (m<sup>3</sup>/s)</b>	48.092
<b>STDEV Observed</b>	23.909
<b>Median observed (m<sup>3</sup>/s)</b>	8.22
<b>Median simulated (m<sup>3</sup>/s)</b>	7.163
<b>STDEV Simulated</b>	14.304
<b>MAE (m<sup>3</sup>/s)</b>	5.41
<b>RMSE (m<sup>3</sup>/s)</b>	10.47
<b>EV (%)</b>	1.46
<b>Nash-Sutcliffe Coefficient (E)</b>	0.69
<b>Index of Agreement (IA)</b>	0.91
<b>Coefficient of Determination (r<sup>2</sup>)</b>	0.6741
<b>Coefficient of Correlation (r)</b>	0.82152

*Source: Researcher (2024)*

As depicted in the table, the validation data for the Kipkaren gauging station (ICE01) from 1990 to 2000 reveals important insights into the performance of the WEAP model. The mean observed flow was 69.118 m<sup>3</sup>/s, while the mean simulated flow was significantly lower at 48.092 m<sup>3</sup>/s, indicating that the model tends to underestimate actual flow rates, as noted by Muhammed *et al.* (2020). Additionally, the standard deviation of the observed flow was 23.909 m<sup>3</sup>/s, reflecting substantial variability, while the simulated flow showed a higher standard deviation of 14.304 m<sup>3</sup>/s. This suggests that the model's predictions fluctuated less than the actual data, which aligns with findings from a number of authors (Okungu *et al.*, 2017).

Further highlighting the discrepancies between the observed and simulated values are the mean absolute error (MAE) of 5.41 m<sup>3</sup>/s and root mean square error (RMSE) of 10.47 m<sup>3</sup>/s. Despite these challenges, several fit statistics indicate good model performance. For instance, the Nash-Sutcliffe coefficient of 0.69, as reported by Reznik *et al.* (2022), suggests acceptable predictive accuracy. Meanwhile, the index of agreement at 0.91 reflects a strong correlation between observed and simulated data. However, the explained variance (EV) of just 1.46% indicates that the model captures only a small portion of the variability in observed flows.

Overall, these findings suggest that while the WEAP model performs reasonably well in simulating hydrological dynamics, there are notable areas for improvement to enhance its accuracy and reliability in the Kipkaren River. This is particularly relevant in light of the implications of land use/land cover changes, as emphasized by Abungba *et al.* (2022), and climate variability (Ahmad and Verma, 2018).

#### 4.2.2 Validation results

To validate the calibrated hydrological model, data for the period from 2001 to 2010 was input and processed to assess model performance, as the calibration had been conducted under normal hydrologic conditions. The results of this model validation are shown in Figure 4.4. At all selected stations, the simulated monthly flows were found to be closely aligned with the naturalized flows.

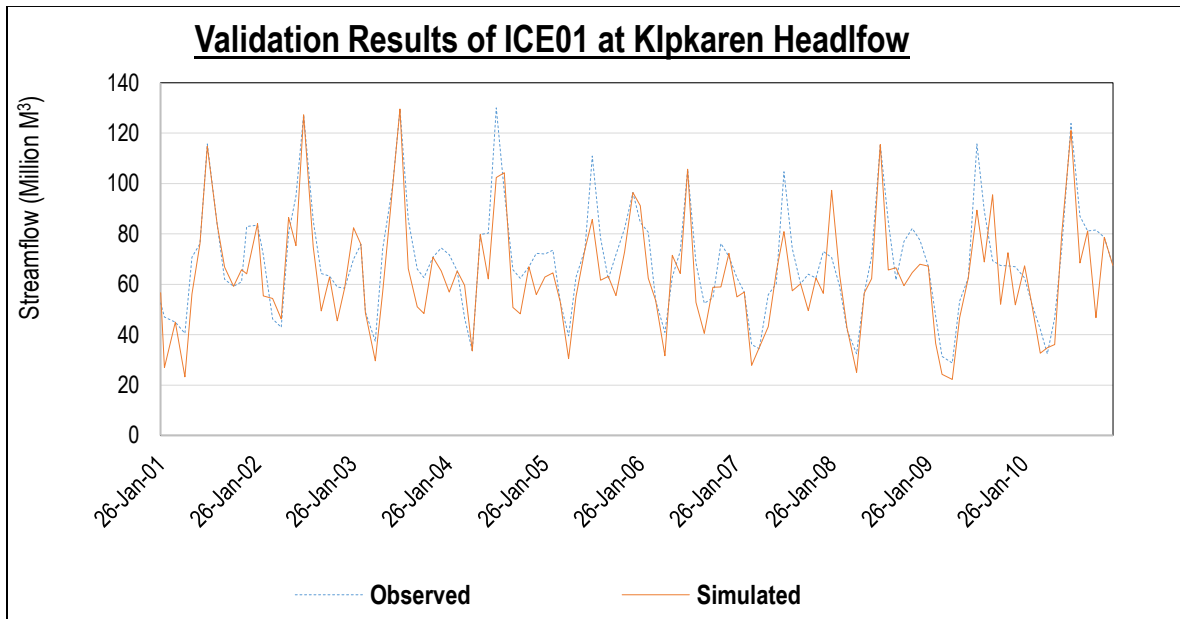


Figure 4.4: Validation results showing observed and simulated stream-flows at selected stations in Kipkaren micro- catchment

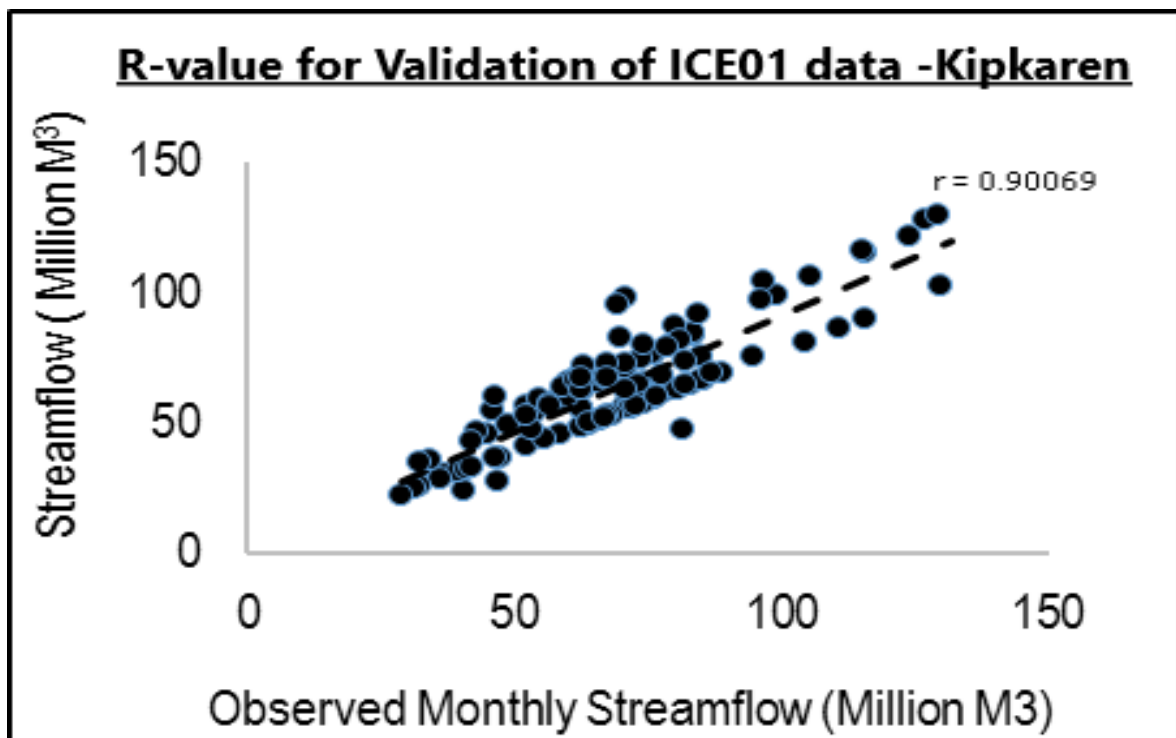


Figure 4.5: Calibration results showing Relationship between monthly observed and simulated streamflow in control stations of Kipkaren micro- catchment .

Table 4.1 presents the **validation** results for the WEAP model at the Kipkaren gauging station (ICE01) for the period from 1990 to 2000. It includes a range of fit statistics that evaluate the model's performance in simulating streamflow data. Key metrics, such as mean observed and simulated flows, standard deviations, and error measurements, are provided to assess the model's accuracy and reliability. Additionally, statistical indicators like the Nash-Sutcliffe coefficient and the index of agreement are included to evaluate the model's ability to replicate observed hydrological dynamics. This analysis is essential for understanding the model's effectiveness in managing water resources within the Kipkaren River.

**Table 4.2:** Fit Statistics of Simulated data by WEAP and Observed Stream Flow data for validation

Fit Statistic	Yala
Mean Observed Flow ( $m^3/s$ )	55.02
Mean Simulated Flow ( $m^3/s$ )	54.09
STDEV Observed	17.09
Median observed ( $m^3/s$ )	53.32
Median simulated ( $m^3/s$ )	50.19
STDEV Simulated	19.89
MAE ( $m^3/s$ )	4.15
RMSE ( $m^3/s$ )	6.67
EV (%)	15.76
Nash-Sutcliffe Coefficient ( $E$ )	1.38
Index of Agreement ( $IA$ )	0.82
Coefficient of Determination ( $r^2$ )	0.8112
Coefficient of Correlation ( $r$ )	0.90069

Source: Researcher (2024)

The validation data for the ICE01 at Kipkaren RGS presented in Table 4.2 offers insights into the performance of the WEAP model for the years 1990 to 2000. The mean observed flow was 55.02  $m^3/s$ , while the mean simulated flow was closely aligned at 54.09  $m^3/s$ , indicating that the model accurately approximates the actual flow rates. As noted by Herman *et al.* (2020), the standard deviation of observed flow was 17.09  $m^3/s$ , reflecting the variability in the data, whereas the simulated flow had a higher standard deviation of 19.89  $m^3/s$ , suggesting that the model's predictions exhibited slightly greater fluctuations than the observed values.

The median observed flow was 53.32  $m^3/s$ , compared to a median simulated flow of 50.19  $m^3/s$ , which again points to a minor underestimation by the model. The mean absolute error (MAE) of 4.15  $m^3/s$  and the root mean square error (RMSE) of 6.67  $m^3/s$  further illustrate

the discrepancies between the observed and simulated flows. Notably, the explained variance (EV) of 15.76% indicates that the model captures a more substantial portion of the variability in observed flows compared to the previous dataset. As highlighted by Mehraban *et al.* (2024), the Nash-Sutcliffe coefficient exceeding 1.0 at 1.38 suggests excellent predictive accuracy, while the index of agreement at 0.82 reflects a strong correlation.

Additionally, the coefficient of determination ( $r^2$ ) of 0.8112 and the coefficient of correlation ( $r$ ) of 0.90069 reinforce the model's effectiveness in simulating the hydrological dynamics of the Yala station.

These findings suggest that the WEAP model performs well in this context, accurately representing the streamflow patterns observed during the validation period. Opoku Oti *et al.* (2020) emphasize that for both calibration and validation processes, the larger values of the Nash-Sutcliffe coefficient (E), coefficient of determination ( $r^2$ ), and correlation coefficient ( $r$ ) demonstrate small differences between simulated and observed values of streamflow data. Therefore, the model's statistical calibration and validation results demonstrate satisfactory performance in reproducing the outputs needed for analyzing scenario results.

### **4.3 Current Water Availability and Demand**

#### **4.3.1 Water Availability**

##### **Annual Total headflow**

The water availability data for the Kipkaren River from 2019 to 2050 provides a comprehensive view of headflow values measured in cubic meters per second (CMS). This dataset shows significant fluctuations in flow across the years, with 2024 recording the highest flow at 554.87 CMS, indicating a period of abundant water availability. Conversely, some years, such as 2020 and 2021, experienced much lower flows at 147.163 CMS and

46.7162 CMS, respectively. This variability underscores the river's susceptibility to changes in climatic conditions and highlights the importance of understanding these patterns for effective water resource management.

Statistical analysis of the data reveals a minimum flow of 6.35178 CMS and a maximum flow of 554.87 CMS, showcasing a broad range in water availability. The mean flow during this period is approximately 125.127 CMS, with a median of 88.1119 CMS. This suggests that while the average flow appears relatively high, many years may experience significantly lower flows, as noted by Okyereh *et al.* (2019). The standard deviation of 116.719 CMS indicates considerable variability in flow rates from year to year. Additionally, the root mean square (RMS) value of 169.865 CMS highlights the average magnitude of the river's flow while accounting for this variability, supporting the findings of Heinzl *et al.* (2022).

These findings illustrate the dynamic hydrological regime of the Kipkaren River , emphasizing the need for adaptive water management strategies to address both potential drought conditions and periods of excessive flow. As highlighted by Rezaei and Alizadeh (2021), effective management in such variable environments is crucial for sustainable water resource utilization. Furthermore, Okungu *et al.* (2017) emphasize the importance of scenario analysis in understanding water supply and demand dynamics, which is essential for informed decision-making in water management.

The water availability for the period 1959-2019 is as illustrated in the figure below:

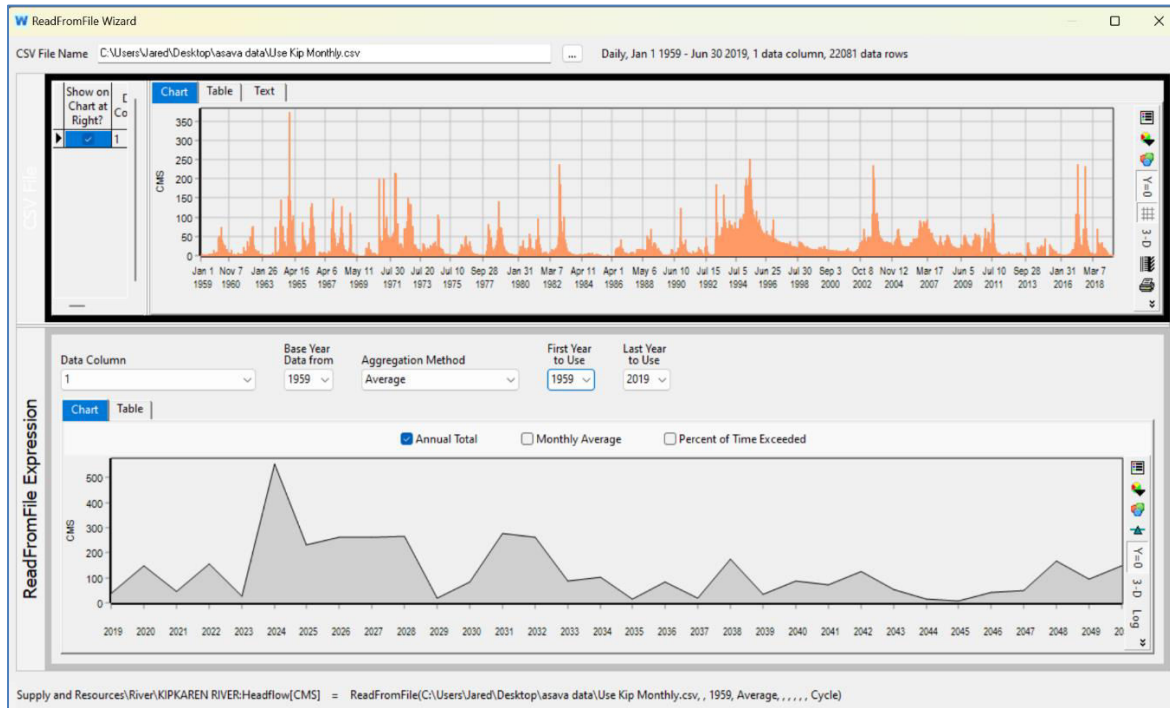


Figure 4.6: Annual total headflow within Kipkaren River for the period 1959-2019

Source: Researcher (2024)

### Monthly Average

The monthly average flow data for the Kipkaren River provides insights into the river's flow patterns throughout the year. Each month's average flow is crucial for understanding seasonal variations in water availability, which are important for resource management.

In January, the average flow is approximately 8.44 CMS, gradually increasing to 11.18 CMS in April, indicating a rise in water levels likely associated with seasonal rainfall. The flow peaks in October at 17.89 CMS, reflecting the high runoff often seen during this period. Conversely, the summer months of July and August show lower averages at 6.38 CMS and 7.32 CMS, respectively, suggesting reduced water availability during these drier months.

The minimum average flow recorded is 6.38 CMS, while the maximum is 17.89 CMS, highlighting the significant range in monthly flow rates. The overall mean flow across the

year is around 10.43 CMS, with a median of 9.73 CMS, indicating that flows are generally moderate. This observation aligns with the findings of Kumar and Bassi (2021), who emphasize the variability in water availability due to climatic extremes. The standard deviation of 3.41 CMS suggests variability in the flow rates throughout the year, underscoring the importance of understanding these patterns for effective water resource planning and management in the Kipkaren River. As noted by Aein and Alizadeh (2021), integrated modeling approaches are essential for optimizing water management strategies in contexts characterized by such variability. Furthermore, Lakshmi (2024) highlights that urban water supply challenges are expected to intensify in the coming decades, reinforcing the need for proactive planning in the Kipkaren area.

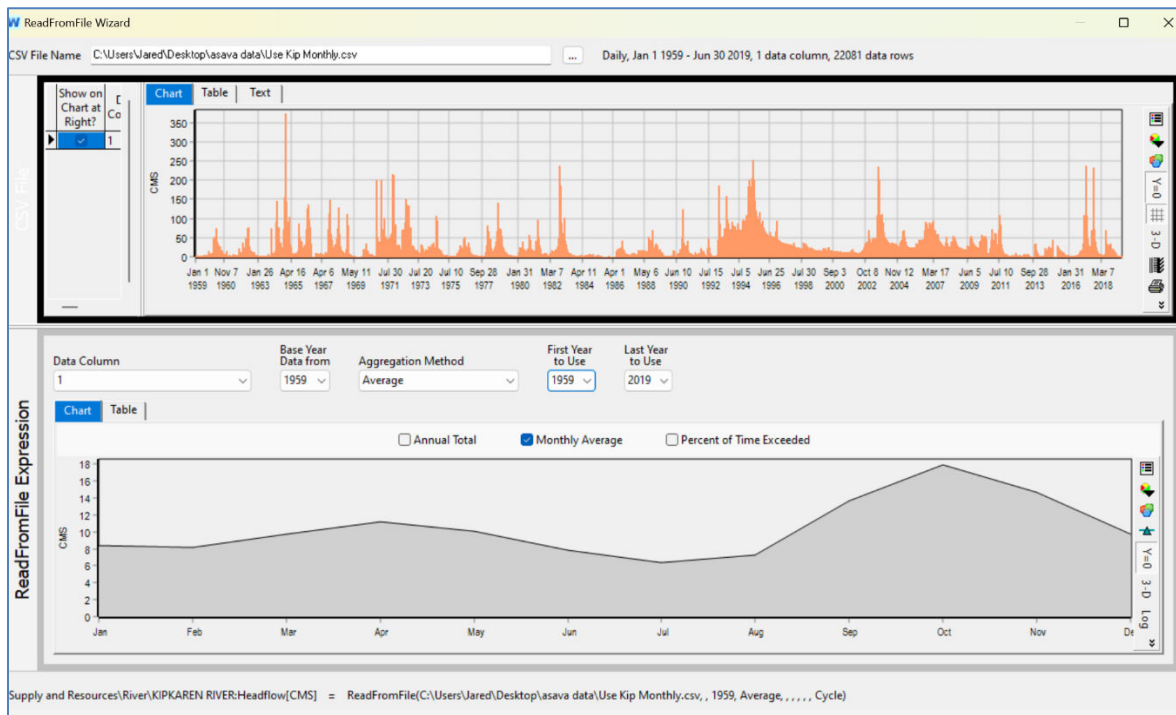


Figure 4.7: Monthly Average flow within Kipkaren River for the period 1959-2019

## **Annual Percentage Exceedance**

The annual percentage exceedance data for the Kipkaren River provides insights into the flow variability and availability over time. The table lists flow values at various exceedance percentages, indicating the flow rate that is equaled or exceeded in that percentage of years.

For example, a 3% exceedance corresponds to a high flow rate of 554.87 CMS, suggesting that this level is only exceeded in very few years, reflecting extreme flood conditions. Conversely, the 97% exceedance level shows a much lower flow rate of 16.37 CMS, indicating that this flow is met or exceeded in the majority of years, representing typical low-flow conditions.

The data reveals a significant range between the minimum and maximum values, with a mean flow of approximately 125.13 CMS. This high variability suggests a dynamic hydrological regime, with potential implications for water resource management, flood risk assessment, and ecological health in the Kipkaren River. As highlighted by Duan *et al.* (2019), understanding these trends is crucial for effectively managing water resources and mitigating the impacts of extreme weather events.

The importance of such analysis is further supported by Kandra and Vyleta (2020), who emphasize the role of modeling in achieving sustainable water management. Similarly, Mehboob *et al.* (2020) demonstrate how modeling water supply and demand can inform decision-making under changing climate conditions. Additionally, the work of Okungu *et al.* (2017) on optimal water allocation models underscores the need for sustainable planning approaches that consider these dynamic hydrological patterns.

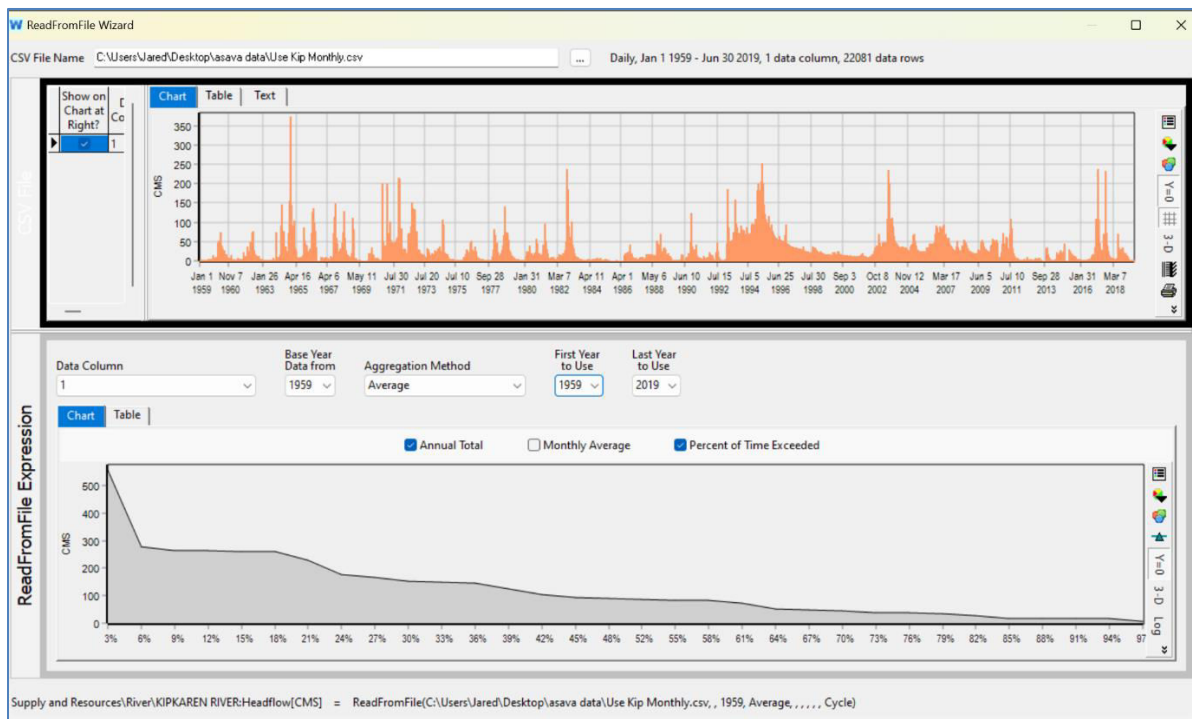


Figure 4.8: Annual Percentage Exceedance within Kipkaren River for the period 1959-2019

The flow criteria for the Kipkaren River indicate significant variations in water availability throughout the year. The reserve flow (Q95) is approximately 6.38 CMS, translating to about 550,752 cubic meters per day, ensuring a reliable base flow for ecological needs. As noted by Okyereh *et al.* (2019), understanding these low flow metrics is critical for maintaining ecological integrity. Normal flow (Q80) peaks in April at 11.18 CMS, or around 965,472 cubic meters per day, reflecting increased water levels due to seasonal rainfall. Conversely, during the summer months, such as July and August, the average flows drop to 6.38 CMS (550,752 CMD) and 7.32 CMS (632,448 CMD), respectively, highlighting reduced availability.

The maximum flow occurs in October at 17.89 CMS, equating to approximately 1,543,056 cubic meters per day, emphasizing the high runoff typical for this period. Remilekun *et al.* (2021) emphasize the importance of seasonal fluctuations in water availability, which can significantly affect resource management strategies. The overall mean flow is about 10.43

CMS (900,192 CMD), with a median of 9.73 CMS (840,192 CMD), indicating moderate water availability across the year. This consistency aligns with the findings of Tena *et al.* (2019), who highlight the relevance of hydrological modeling in assessing water resources. Understanding these metrics is crucial for effective water resource planning and management in the region, as supported by Rezaei and Alizadeh (2021), who discuss integrated modeling approaches for optimizing water resources.

### 4.3.2 Current water demand

#### Domestic Water Demand

Table 4.3 presents an overview of domestic water demand in the Kipkaren River region for the year 2019. It categorizes different areas based on their urban or rural classification, detailing the population, allocated water per capita, and the total daily water demand.

*Table 4.3: Domestic Population and Water Demand*

Area	Class	Population (2019)	Qty of Water Allocated (L/day)	Water Demand (m <sup>3</sup> /day)
Lumakanda	Urban (Low density population)	50,000	20	1,000
Kipkaren	Urban (Low density population)	101,800	20	2,036
Turbo	Urban (Low density population)	57,000	50	2,850
Lwandeti	Rural Medium Potential	37,700	50	1,885
Other areas	Rural Medium Potential	40,500	50	2,025
<b>Total</b>		<b>287,000</b>	<b>Total</b>	<b>9,796</b>

*Source: Researcher (2024)*

The total domestic population in the Kipkaren River region is 287,000, with a collective daily water demand of approximately 9,796 m<sup>3</sup>. Urban areas, particularly Kipkaren and Turbo, exhibit substantial demand, with Turbo needing a higher allocation of 50 liters per person. Rural areas like Lwandeti and others also utilize 50 liters per person, resulting in

significant total demands. This data is essential for planning and managing water resources to ensure that all communities have adequate access to water.

### **Institutional Water Demand**

Table 4.4 provides insights into the water demand from various institutional sectors, including educational institutions, health facilities, and commercial establishments for the year 2019. It details the number of institutions, their respective water requirements, and the total daily water demand.

*Table 4.4: Institutional Population and Water Demand*

<b>Category</b>	<b>Description</b>	<b>Units (2019)</b>	<b>Unit Water Requirement (L/institution)</b>	<b>Total Water Demand (m<sup>3</sup>/day)</b>
Schools	Boarding schools	7	30,000	210
	Day schools	36	14,000	504
	Colleges	4	10,000	40
Health Facilities	Health facilities	7	10,000	70
Commercial Facilities	Hotels and restaurants	32	3,000	96
	Shops and other	39	1,000	39
	Milk cooling plants/factories	11	800	8.8
Other	Administrative Offices/etc	13	1,200	15.6
<b>Total</b>				<b>983.4</b>

*Source: Researcher (2024)*

The total water demand from institutional sectors amounts to approximately 983.4 m<sup>3</sup> per day. Schools represent a significant portion of this requirement, particularly day schools and boarding schools, necessitating substantial water supplies for educational purposes. As noted by Okungu (2018), these institutions often require reliable water access to support their operations effectively. Health facilities also demand considerable amounts of water, highlighting the critical need for hygiene and care in healthcare settings. This aligns with the findings of Phan *et al.* (2021), who emphasize the importance of ensuring adequate water

resources in institutional contexts to maintain health and sanitation. Additionally, commercial enterprises contribute to the overall demand, underscoring the diverse water needs of the community. The work of Poblete *et al.* (2023) further illustrates the significance of participatory water resources modeling to address varying demands in local contexts. Overall, this data underscores the necessity of ensuring adequate water availability to support these essential institutions effectively.

### **Agricultural Requirement and Livestock Water Demand**

This table focuses on the water requirements for agricultural activities and livestock in the Kipkaren River region for the year 2019. It details the water demand for irrigation and livestock, providing a clear understanding of the agricultural sector's dependence on water resources (Table 4.5).

*Table 4.5: Agricultural Requirement and Livestock Water Demand*

<b>Category</b>	<b>Description</b>	<b>Quantity</b>	<b>Unit Demand (2019) (L/day)</b>	<b>Total Water Demand (m<sup>3</sup>/day)</b>
Irrigation	Number of ha	20,000	5,000	100,000
Livestock	Number of livestock	10,000	20	200
<b>Total (m<sup>3</sup>/day)</b>				<b>100,200</b>

*Source: Researcher (2024)*

The agricultural sector has a total water demand of approximately 100,200 m<sup>3</sup> per day, primarily driven by irrigation needs across 20,000 hectares and the requirements of 10,000 livestock. The irrigation alone demands a staggering 100,000 m<sup>3</sup> daily, highlighting the essential role of water in sustaining agricultural productivity. Meanwhile, livestock needs contribute an additional 200 m<sup>3</sup> per day. This data is crucial for understanding the significant reliance of the agricultural sector on water resources, which is vital for food security and economic stability in the region.

The total water demand in the Kipkaren River region for 2019 is significant, reflecting the diverse needs of its population and sectors. The domestic population of 287,000 requires approximately 9,796 m<sup>3</sup> per day, with urban areas like Kipkaren and Turbo showing particularly high demand due to their larger populations. This high demand aligns with findings from the Stockholm Environment Institute, which emphasizes the challenges faced by urban centers in managing water resources effectively. Institutional needs contribute an additional 983.4 m<sup>3</sup> per day, driven mainly by schools, health facilities, and commercial establishments. Mumbi *et al.* (2021) highlight the importance of forecasting water consumption to enhance management strategies in these contexts.

The agricultural sector, primarily for irrigation and livestock, demands a substantial 100,200 m<sup>3</sup> per day, underscoring its critical reliance on water for productivity. As discussed by Leong and Lai (2017), effective integrated water resources management is essential for supporting such significant agricultural demands. Collectively, these figures underscore the pressing need for effective water resource management to ensure sustainable access across all community sectors, as reiterated by Okungu *et al.* (2017), who advocate for optimal water allocation models to support sustainable planning.

#### **4.4 Scenario Analysis**

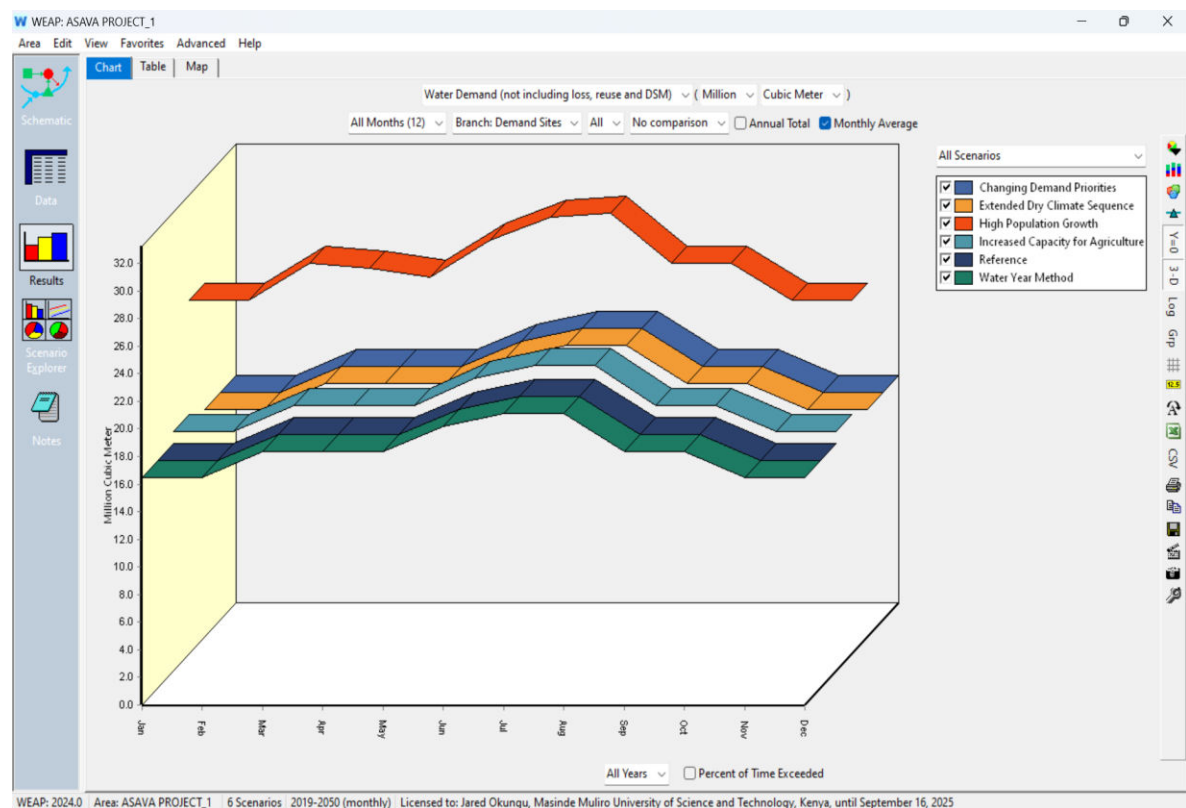
##### 4.4.1 Introduction

This section focuses on simulating water supply and demand in the Kipkaren River within the Upper Nzoia Catchment using the WEAP model. Given the increasing constraints on water resources from population growth and agricultural demands, understanding various scenarios is essential. The study examines the following scenarios: (i) the **Current Accounts Scenario**, which establishes a baseline for 2019; (ii) the **Reference Scenario**, projecting supply and demand from 2020 to 2050 with a 2.51% population growth rate; (iii) the **High**

**Population Growth Scenario**, which increases the growth rate to 5.0%; (iv) the **Wet Climate Scenario**, evaluating how climate variations impact water availability; (v) the **Extended Dry Climate Sequence**, considering the effects of sustained low water availability; and (vi) the **Increased Capacity for Agriculture Scenario**, which explores the implications of expanding irrigation and livestock production on water demand. This analysis aimed to provide insights for effective water resource management in the Kipkaren River basin.

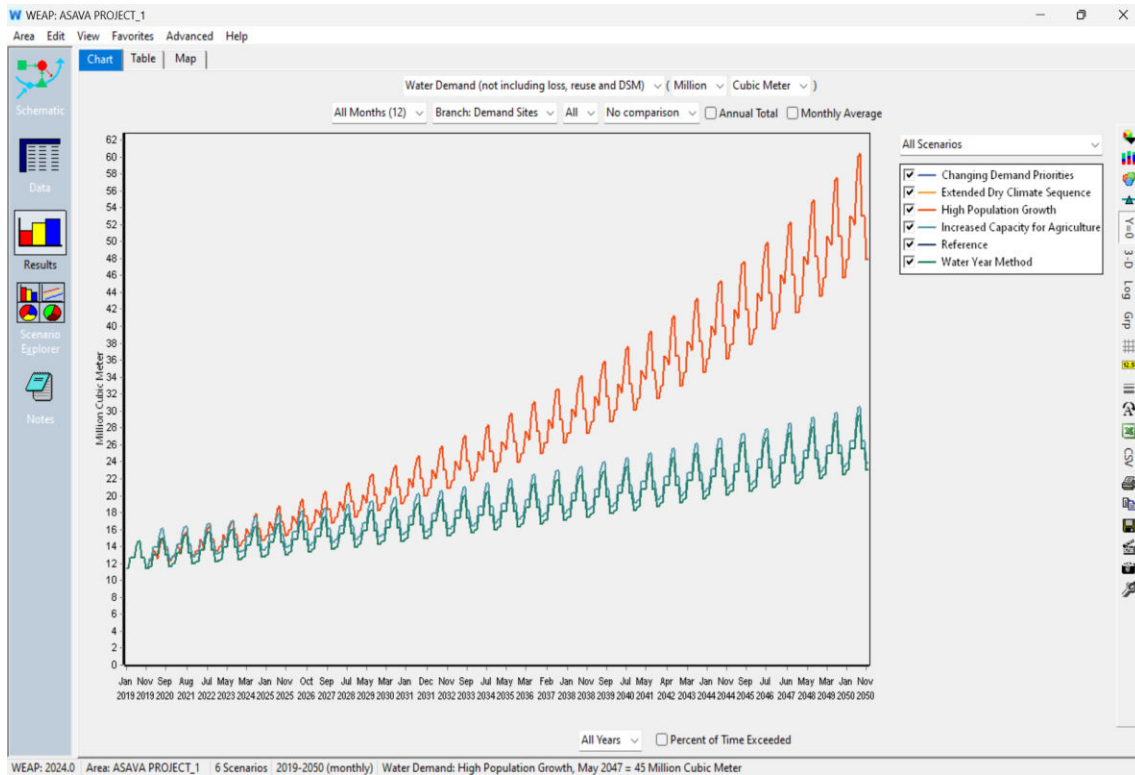
#### 4.4.2 Water Demand based on All Scenarios for all Demand Sectors (2020 - 2050)

The projected water demand across all sectors—domestic, agricultural, and institutional—reveals significant trends and challenges from 2020 to 2050 (Figure 4.9).

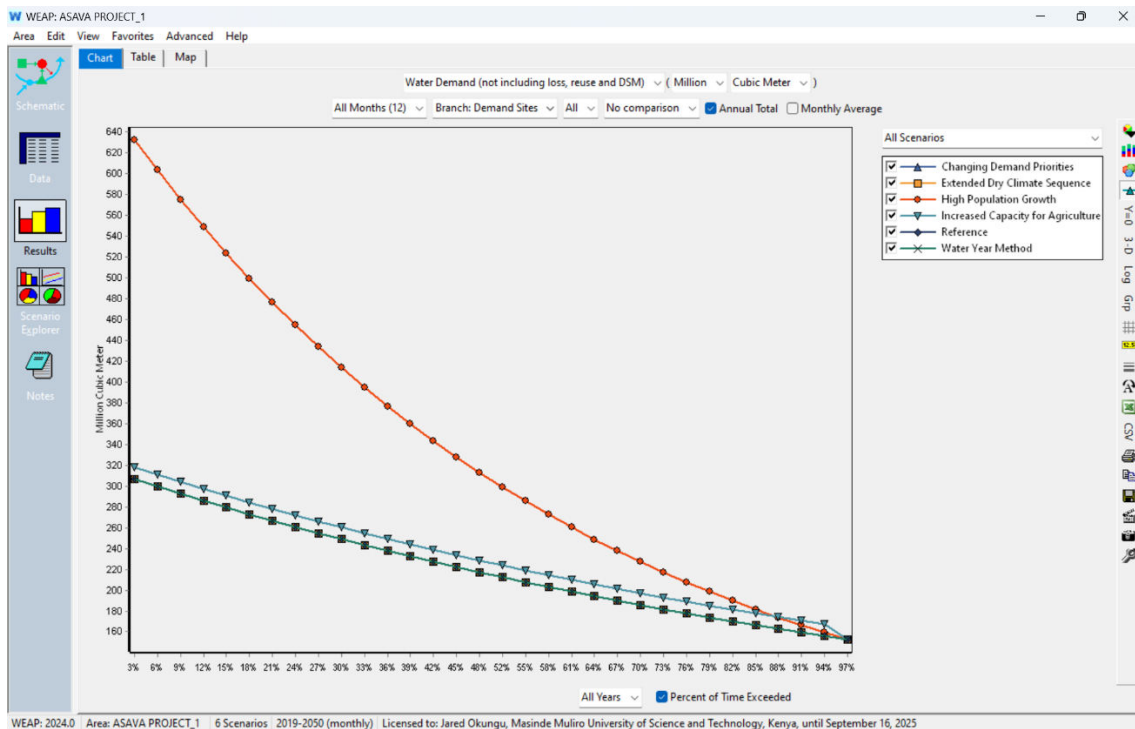


**Figure 4.9: Monthly Average Water Demand (2020-2050) - Based on all the Scenarios**

Source: Researcher (2024)



**Figure 4.10: All-Year (2020-2050) Water Demand - Based on all the Scenarios**

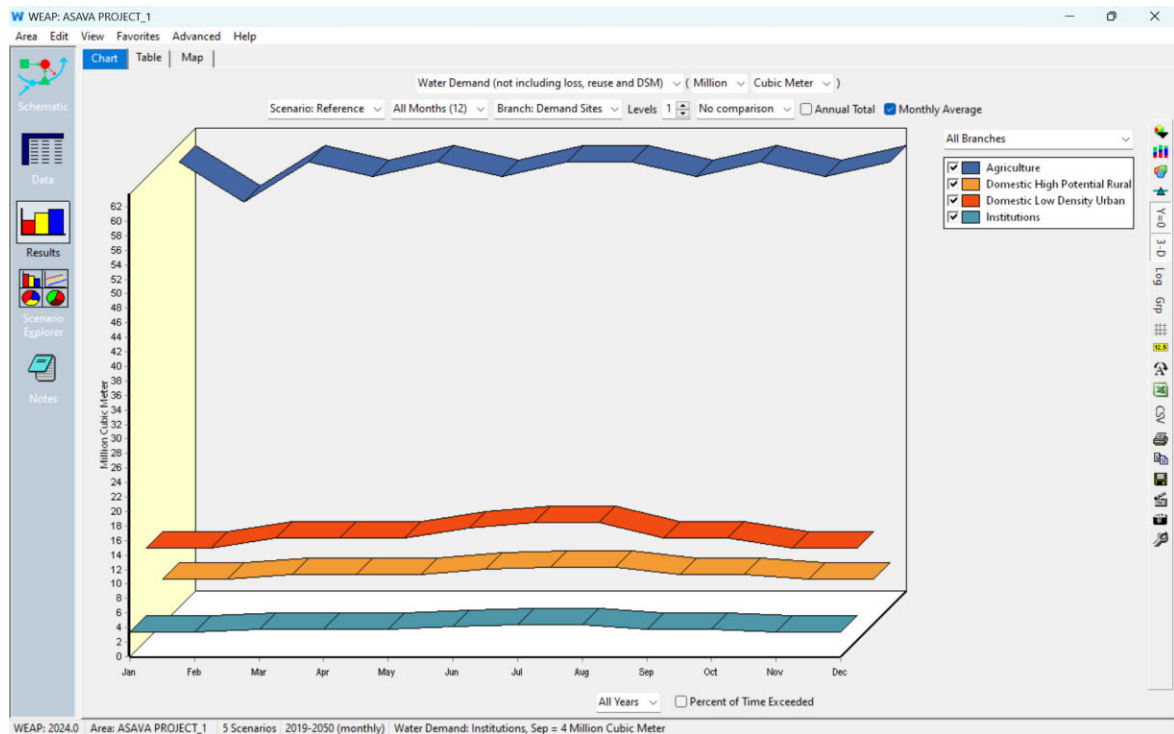


**Figure 4.11: Average Percentage Time Exceedance of Water Demand (2020-2050) - Based on all the Scenarios**

From Figure 4.9 – 11, the **Reference Scenario**, incorporating a 2.51% population growth rate, for the period 2020-2050 indicates a steady rise in demand, underscoring the necessity for enhanced management practices, particularly during peak periods when supply may be inadequate. Conversely, the **High Population Growth Scenario**, with a growth rate increased to 5.0%, shows a marked surge in domestic water requirements, potentially leading to shortages and emphasizing the urgent need for effective management strategies. In the **Wet Climate Scenario**, while increased rainfall may enhance water availability during certain years, the variability necessitates robust practices to capture excess water for drier periods. The **Extended Dry Climate Sequence** predicts sustained low water availability, leading to increased competition among sectors and a shift in demand priorities, with a focus on conservation and adaptive management. Lastly, the **Increased Capacity for Agriculture Scenario** anticipates significant growth in agricultural water demand due to expanded irrigation and livestock production, which could strain available resources and create conflicts with domestic and institutional needs. Overall, these scenarios suggest that water demand will increase substantially over the coming decades, necessitating proactive strategies to balance supply and demand and ensure sustainable water use in the Kipkaren River basin.

#### **4.4.3 Reference Scenario (2020-2050)**

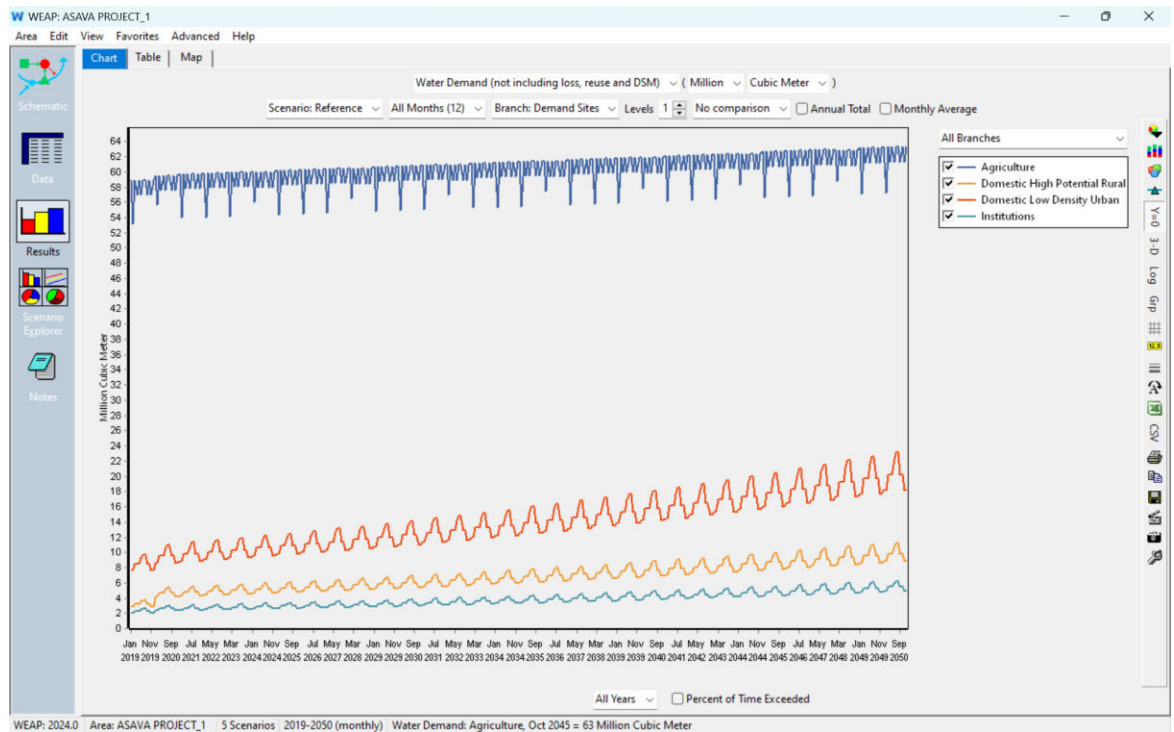
The study set **Reference Scenario** which projects water supply and demand from a period of **2020 to 2050**, incorporating a population growth rate of **2.51%** based on geometric progression growth rate of the Kenya Population Census report of **2019**. This scenario emphasizes the relationship between population growth and increased water needs, particularly in domestic and agricultural sectors (Figure 4.12).



**Figure 4.12: Monthly average water demand (2020-2050) under Reference Scenario for all demand sites**

Source: Researcher (2024)

The data illustrated in Figure 4.12 shows monthly average water demand across various sectors in the Reference Scenario, highlighting that agriculture is the dominant sector with a total demand of 722.45 million cubic meters. This sector consistently uses around 61 million cubic meters monthly, indicating its dependence on stable water supply for irrigation. The Domestic High Potential Rural sector demands 81.81 million cubic meters, with higher usage during wetter months. The Domestic Low Density Urban sector has a total demand of 168.73 million cubic meters, reflecting significant urban water needs, while the Institutional sector has the lowest demand at 45.62 million cubic meters. Overall, total water demand across all sectors reaches 1,018.62 million cubic meters annually, with peaks during wetter months, underscoring the critical role of agriculture in water demand and the need for effective resource management to balance sectoral needs.



**Figure 4.13: Annual average water demand (2020-2050) under Reference Scenario for all demand sites**

*Source: Researcher (2024)*

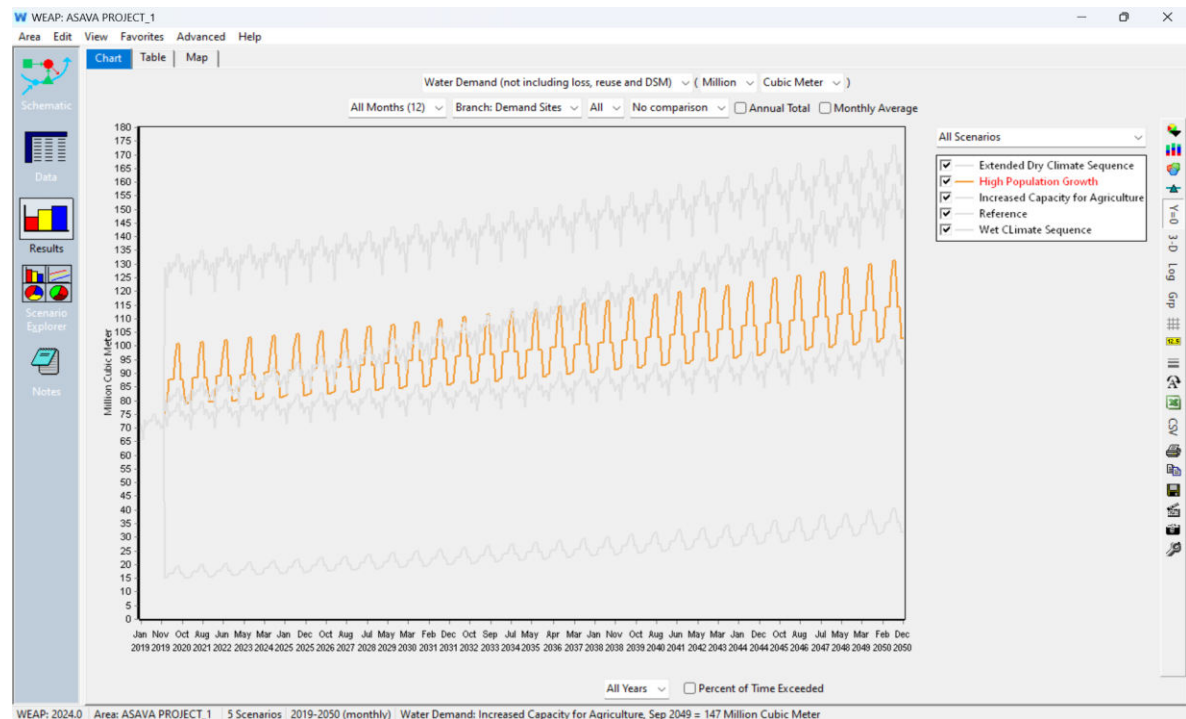
The scenario depicted in Figure 4.13 serves as a baseline, starting with values around 70.9 million and growing slowly to approximately 96.7 million by April 2050. The gradual increase indicates stability and reflects a situation without extreme climatic or demographic changes. This scenario can be viewed as an ideal management state, where resources are effectively managed under current conditions. It underscores the importance of maintaining balance and efficiency in resource use to avoid the pitfalls seen in more extreme scenarios.

The findings reveal critical periods when water demand may exceed available supply, supporting assertions made by the International Water Management Institute (2021) that proactive water management strategies are essential in regions facing water scarcity. By identifying these peak demand periods, stakeholders can better prepare for potential water shortages and develop policies that balance supply and demand effectively, as highlighted

by Remilekun *et al.* (2021), ensuring sustainable water use in the region over the long term. Furthermore, Limantara *et al.* (2024) emphasize the importance of performance index models in water allocation, which can facilitate effective management during these critical times. Overall, the need for integrated approaches, such as those proposed by Wu *et al.* (2023), is evident, as they advocate for optimal water resource allocation to address both current and future challenges in water-scarce areas.

#### 4.4.4 High Population Growth Scenario

The study set the **High Population Growth Scenario**, with the assumption that the domestic demand growth rate would be increased to **5.0%** from 2.51% of Reference Scenario, reflecting a more aggressive population growth trajectory. This analysis was expected to reveal the significant impact that a heightened demand would have on the region's water resources (Figure 4.14).



**Figure 4.14: High Population Growth Scenario (2020-2050) across all demand sites**

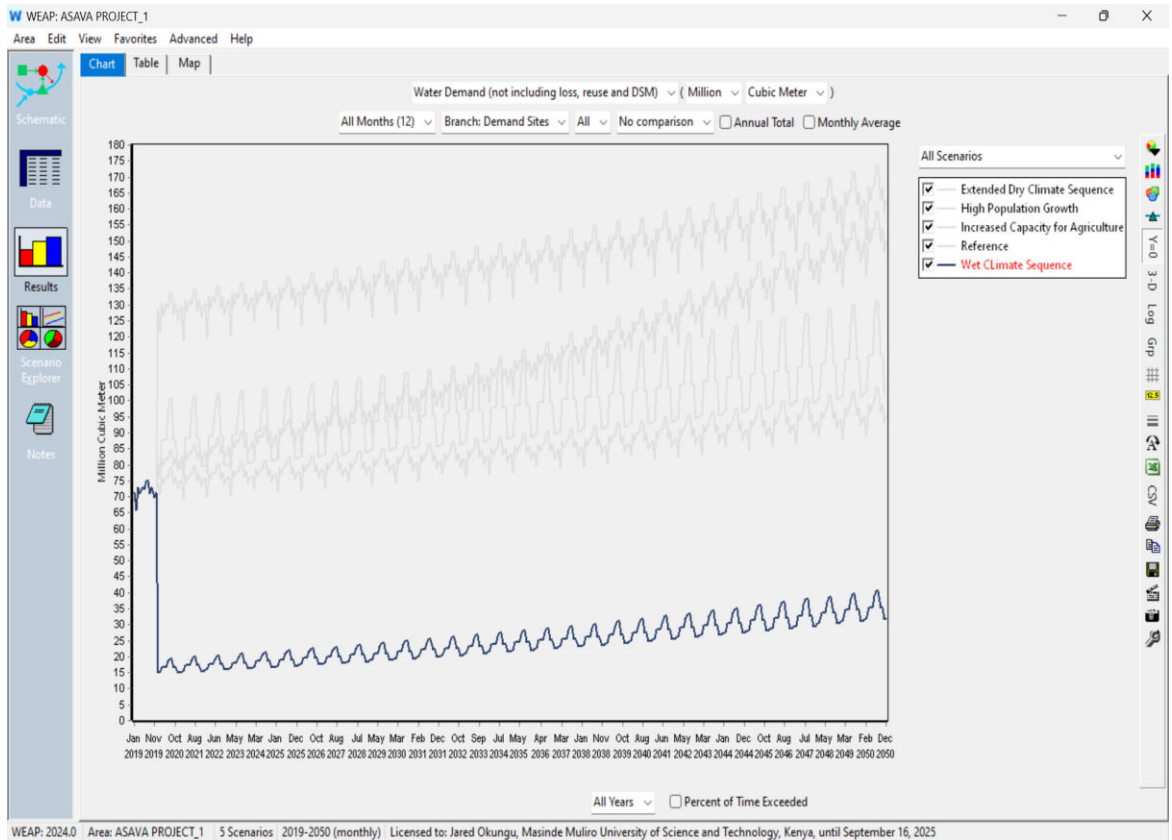
Source: Researcher (2024)

In this scenario (Figure 4.14), initial values are similar to the dry climate sequence but show slower growth. However, as time progresses, especially from 2025 onward, the numbers increase significantly, reaching over 112 million by April 2050. This reflects the rising demand for water and resources due to population pressures. The implications are clear: higher population density will require enhanced water supply systems, improved infrastructure, and sustainable agricultural practices to meet the growing needs. Policymakers must consider how to balance resource availability with population growth to ensure water security.

The results of this scenario suggest that as the population in the Kipkaren River increases, water demand will escalate considerably, supporting the findings of Okungu *et al.* (2017), who noted similar trends in the Yala Catchment. The growing need for domestic, agricultural, and industrial water could outstrip the river's capacity, especially if infrastructure to manage this demand is not developed, as highlighted by Chadwick *et al.* (2021), who emphasized the importance of proactive management in adapting to changing water availability. This resultant pressure could lead to unsustainable water withdrawal practices, compromising the river's health and the communities relying on it for their livelihoods, which aligns with the concerns raised by Asghar *et al.* (2019) regarding the need for integrated hydrological modeling to assess and address water supply and demand under various scenarios.

#### **4.4.5 Wet Climate Scenario**

The study set a **Wet Climate Scenario**, which would employ a Water-Year methodology to analyze the implications of varying climate conditions, specifically focusing on periods characterized by higher precipitation. By categorizing years into very dry, dry, normal, or very wet conditions, this analysis assessed how climate variability would influence water availability in the Kipkaren River River (Figure 4.15).



**Figure 4.15: Wet Climate Scenario (2020-2050) across all demand sites**  
 Source: Researcher (2024)

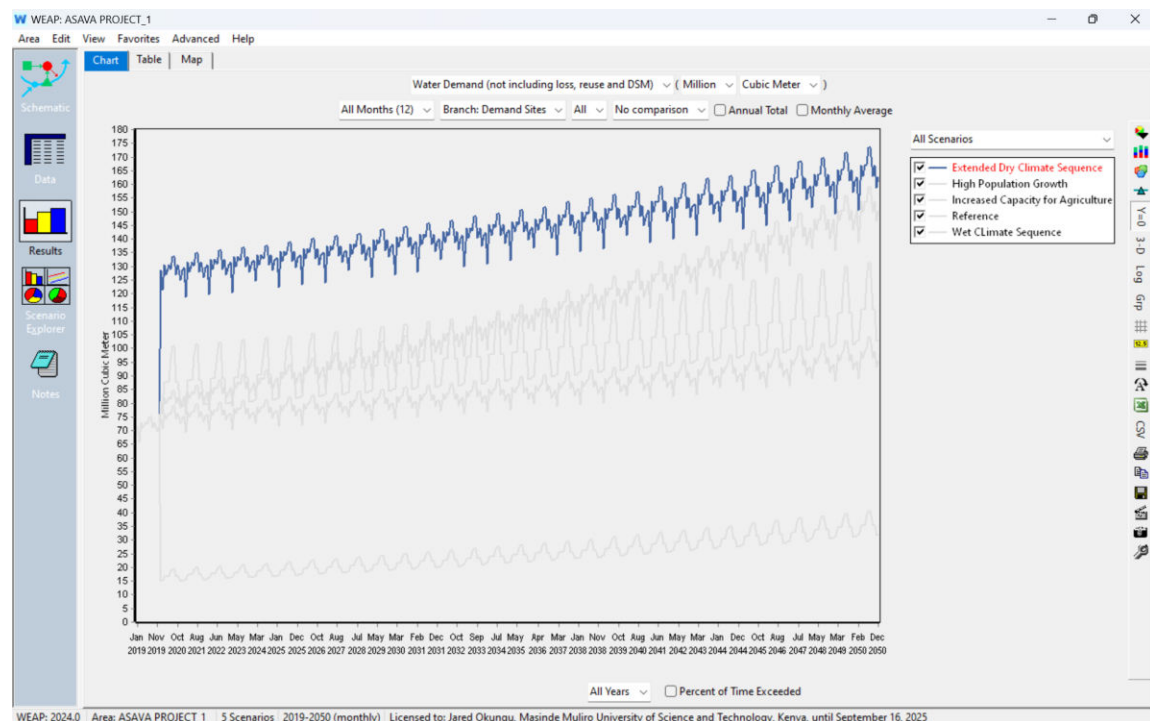
This scenario (Figure 4.15) starts at similar levels but experiences a sharp decline in the early 2020s before rising again, ultimately reaching around 354 million by April 2050. The initial drop may suggest a phase of instability or variability in water resources, possibly due to flooding or excessive rainfall that disrupts water management systems. However, the subsequent growth indicates that wet conditions can lead to increased water availability over time. This scenario highlights the need for adaptive management to harness excess water during wet periods while preparing for potential flooding and related challenges.

In this scenario, the results imply that initial periods of water abundance could lead to fluctuating demand patterns, which supports Brown *et al.* (2019), who discuss the challenges of managing water resources under conditions of variability. If the Kipkaren River experiences periods of high flow followed by scarcity, as highlighted by Herman *et al.*

(2020), it may complicate planning and allocation efforts, making adaptive management essential. While the potential for increased availability could support agricultural expansion or other water-intensive uses, the variability could also lead to inefficiencies and mismanagement, echoing the concerns raised by Duan *et al.* (2019) regarding the need for integrated approaches to manage the water-climate-food nexus effectively. This emphasizes the urgent need for adaptive strategies to manage both surplus and deficits effectively, as outlined in the findings from Leong and Lai (2017), who stress the importance of integrated water resources management.

#### 4.4.6 Extended Dry Climate Sequence

Assuming a prolonged dry climate from 2020 to 2050, the study set Extended Dry Climate Sequence Scenario in order to critically evaluates the implications of sustained low water availability within the Kipkaren River (Figure 4.16).



**Figure 4.16: Extended Dry Climate Sequence (2020-2050) across all demand sites**  
 Source: Researcher (2024)

This scenario (Figure 4.16) illustrates the effects of a prolonged dry climate on resource availability. Starting at around 70.9 million, values increase steadily to over 162 million by April 2050. This upward trend suggests that persistent drought conditions will strain water resources and agricultural productivity, making it crucial to develop strategies for water conservation and efficient resource management. The gradual increase highlights the long-term implications of sustained dry spells, which could lead to decreased agricultural yields and increased competition for water among various sectors.

From the results of this scenario, the persistent dry conditions would likely lead to a significant increase in water demand, supporting the findings of Abungba *et al.* (2022), who note that limited supply exacerbates competition among users. As agricultural activities and domestic needs struggle to meet the constrained supply, the heightened demand could potentially lead to conflicts, as highlighted by Chepyegon and Kamiya (2018) in their examination of challenges in water sector management. For the Kipkaren River, which may experience reduced flow due to prolonged drought, this situation could increase the risk of over-extraction and ecological degradation, impacting both human and environmental needs, echoing the concerns raised by Chadwick *et al.* (2021) regarding the necessity for adaptive water management in response to climate change. Furthermore, the importance of infrastructure improvements and effective governance in mitigating these risks is emphasized by Jeuland *et al.* (2021) and Juma *et al.* (2022), who suggest that enhancing water management practices can alleviate pressures on water resources.

#### **4.4.7 Increased Capacity for Agriculture**

The study set up the possibility of **Increased Capacity for Agriculture Scenario** by about 50% of Agricultural coverage, within the period covered by current accounts. It investigates the effects of expanding irrigation and livestock production on water demand. The scenario

simulates changes in agricultural practices, this analysis explores the trade-offs between agricultural water needs and those of domestic and institutional sectors (Figure 4.17).



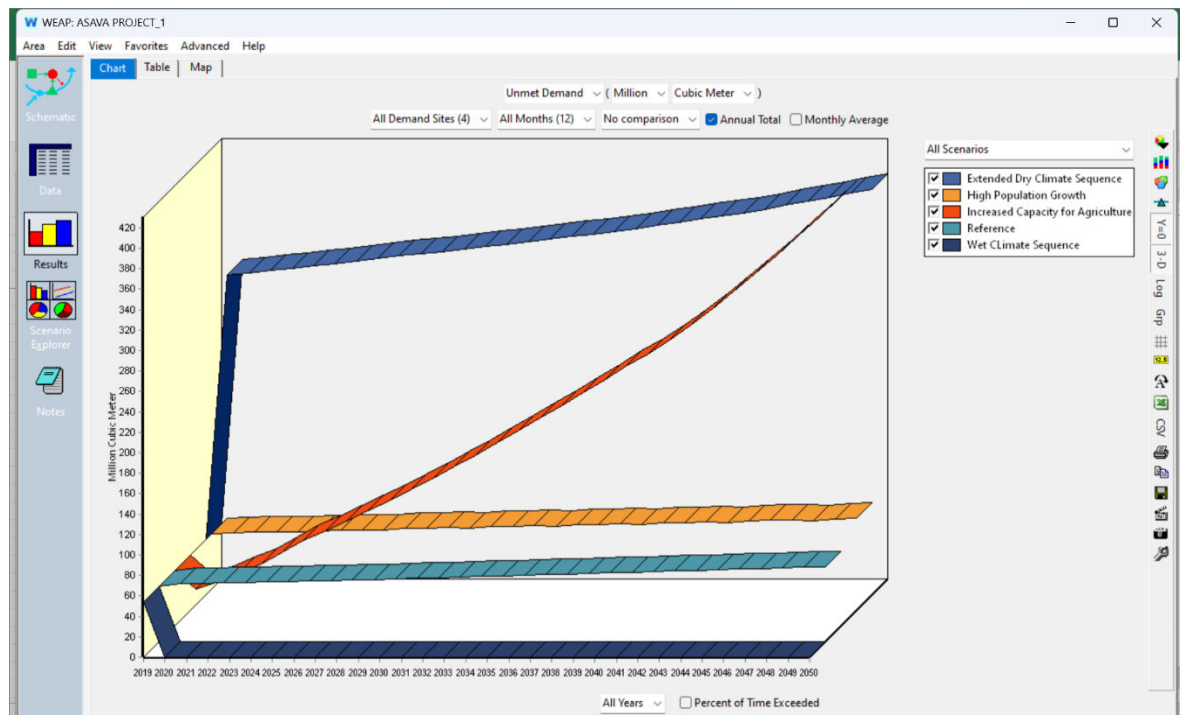
**Figure 4.17: Increased Capacity for Agriculture (2020-2050) across all demand sites**  
Source: Researcher (2024)

From Figure 4.17, beginning at a similar level to the other scenarios, this one displays a more moderate increase in values, peaking at around 149 million by April 2050. The slower growth suggests that while agricultural capacity is enhanced, it still faces limitations due to external factors such as climate variability. The ability to adapt agricultural practices can help alleviate some resource stress, indicating a pathway toward improved sustainability. This scenario highlights the importance of investing in agricultural technology and practices that optimize water use and increase resilience against climatic challenges.

The findings suggest that while this scenario proposes enhanced agricultural practices, it also indicates a specific demand for water resources to support these improvements. If these practices are not water-efficient, as noted by Abbas *et al.* (2022), the increased capacity could

lead to a higher overall water demand. Conversely, if the innovations result in more effective water use, this scenario might mitigate some negative impacts, allowing for more sustainable extraction from the Kipkaren River . However, Agarwal *et al.* (2019) caution that if demand continues to rise faster than the river's replenishment rate, it could strain the system, highlighting the critical balance required in water management. Additionally, the conjunctive management strategies discussed by Dehghanipour *et al.* (2019) illustrate the importance of integrating various water sources to meet demand, emphasizing the need for adaptive approaches in semi-arid regions. Overall, the implications underscore the necessity of adopting water-efficient practices to ensure the long-term sustainability of water resources in the catchment.

## Unmet demand

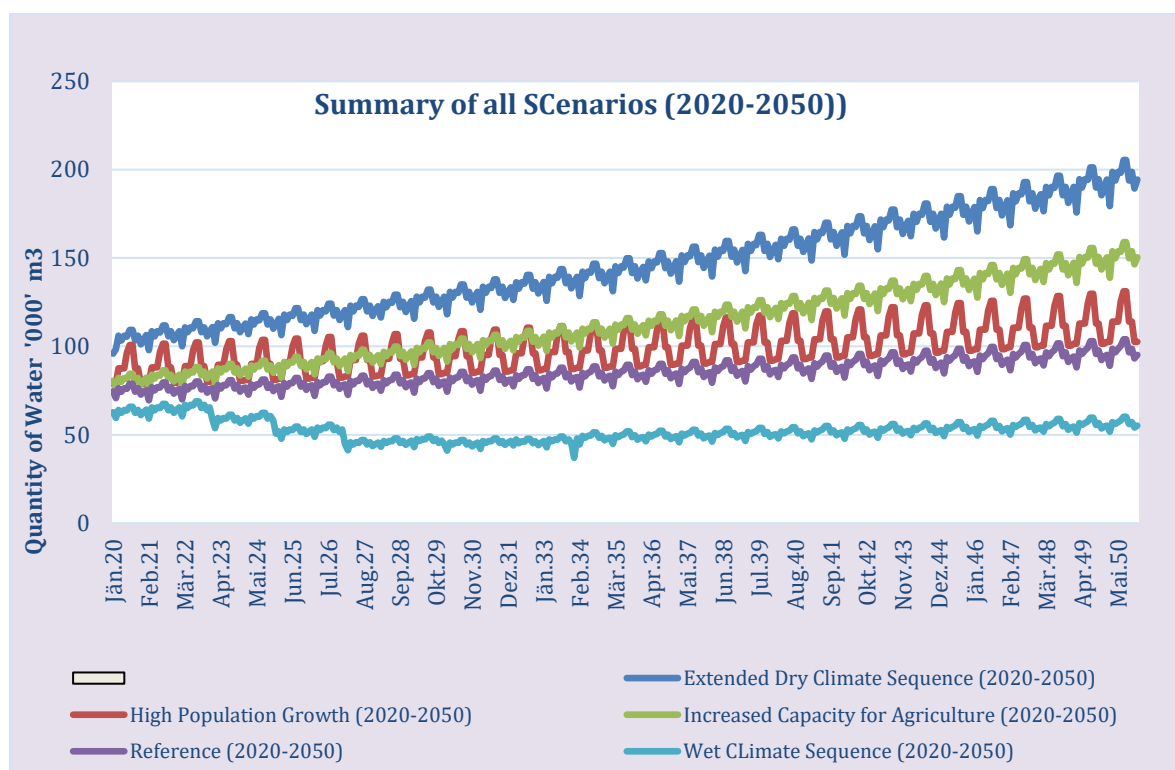


**Figure 4.18: Summary of unmet Demand (2020-2050) across all demand sites**

Source: Researcher (2024)

The results imply that, based on available water in 2019, unmet demand would occur between 2019 and 2050 across various scenarios. The **Extended Dry Climate Sequence** showed the highest unmet demand at  $1.09 \times 10^{10}$  Mm<sup>3</sup>, with peaks in 2028 and 2030. The **High Population Growth scenario** indicated  $2.61 \times 10^6$  Mm<sup>3</sup>, and the **Increased Capacity for Agriculture scenario** totaled  $6.33 \times 10^6$  Mm<sup>3</sup>. The **Reference Scenario** had unmet demand of  $2.05 \times 10^6$  Mm<sup>3</sup>, while the **Wet Climate Sequence** reflected unmet demand only in 2019.

#### 4.4.8 Summary for all Scenarios



**Figure 4.19: Summary of All Scenarios (2020-2050) across all demand sites**

As illustrated in Figure 4.18., when comparing water demand behaviors across scenarios in relation to the Reference Scenario, notable differences emerge. The Extended Dry Climate Sequence indicates a sharp increase in water demand over time, as persistent drought

conditions create heightened competition for limited water resources, contrasting sharply with the Reference Scenario's steady and manageable growth.

In the High Population Growth scenario, water demand initially aligns with the Reference Scenario but accelerates significantly in later years, reflecting the mounting pressures of a growing population that could strain available resources. This observation supports the assertions made by the International Water Management Institute (2023) regarding the increasing challenges posed by population growth on water scarcity.

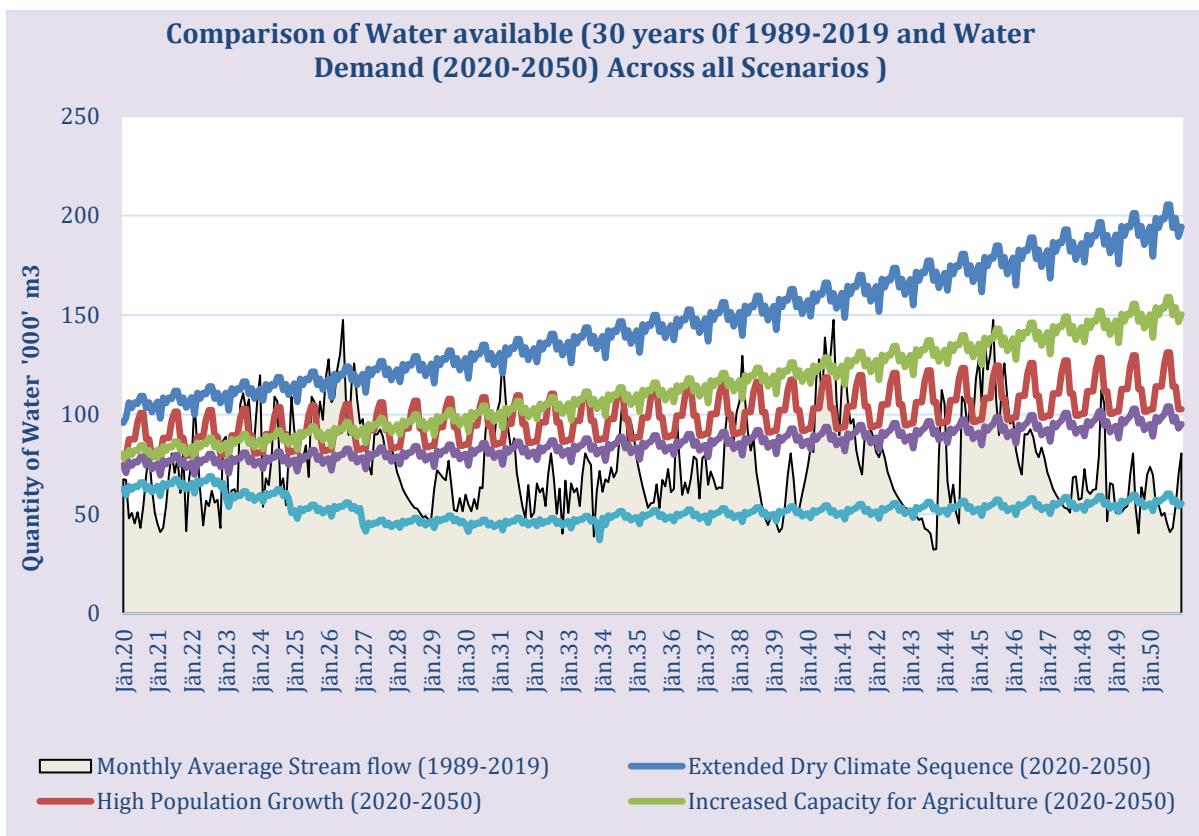
The Increased Capacity for Agriculture scenario, on the other hand, exhibits a more moderate increase in water demand, suggesting that enhanced agricultural practices may improve efficiency, although it still fails to reach the stability seen in the Reference Scenario. This aligns with findings by Fanta *et al.* (2022), which emphasize the need for effective water management strategies to address agricultural water demands. Meanwhile, the Wet Climate Sequence presents a complex picture: while it may initially suggest reduced water demand due to overabundance, the variability in conditions can lead to both surpluses and deficits, creating an unpredictable demand pattern that contrasts with the stable trajectory of the Reference Scenario.

According to Juma *et al.* (2022), this variability underscores the importance of adaptive water management practices in responding to changing climatic conditions. Overall, these findings indicate that the Reference Scenario serves as a benchmark for sustainable water demand, while the other scenarios highlight the varying challenges and pressures that could impact water availability and management strategies.

## 4.5 Water Supply Requirements (Water Allocation) for Demand Sites for 2020-2050

### 4.5.1 Allocable Water (Supply Requirement) of All Scenarios (2020-2050)

In order to determine optimal water allocation within the catchment using the WEAP Model, supply requirement data for the Kipkaren River from 2020 to 2050 was examined by WEAP so as to offer valuable insights into the future of water demand across various scenarios. Each scenario reflects different environmental and socio-economic conditions, highlighting the need for tailored management strategies as depicted in Figure 4.19



**Figure 4.20: Allocable Water (Supply Requirement) of All Scenarios (2020-2050) across all demand sites**

Source: Researcher (2024)

According to results illustrated by Figure 4.19, the supply requirement data for the Kipkaren River from 2020 to 2050 reveals key trends across various scenarios, each highlighting distinct water management challenges.

**Extended Dry Climate Sequence:** Water demand is projected to rise sharply from 71 million cubic meters in 2019 to around 163 million by 2050. This highlights the urgent need for effective conservation strategies and innovative approaches to manage water scarcity in drought conditions.

**High Population Growth:** This scenario anticipates a gradual increase in demand, reaching about 114 million cubic meters by 2050. The rising population will strain existing water resources, necessitating enhanced infrastructure and public awareness campaigns for water conservation.

**Increased Capacity for Agriculture:** This scenario predicts an even steeper rise, with demand increasing to approximately 170 million cubic meters by 2050. It emphasizes the importance of sustainable agricultural practices, such as adopting drought-resistant crops and improving irrigation efficiency.

**Reference Scenario:** Reflecting moderate growth, this scenario serves as a stable baseline for comparing other scenarios, allowing stakeholders to assess the effectiveness of management strategies and identify potential water stress.

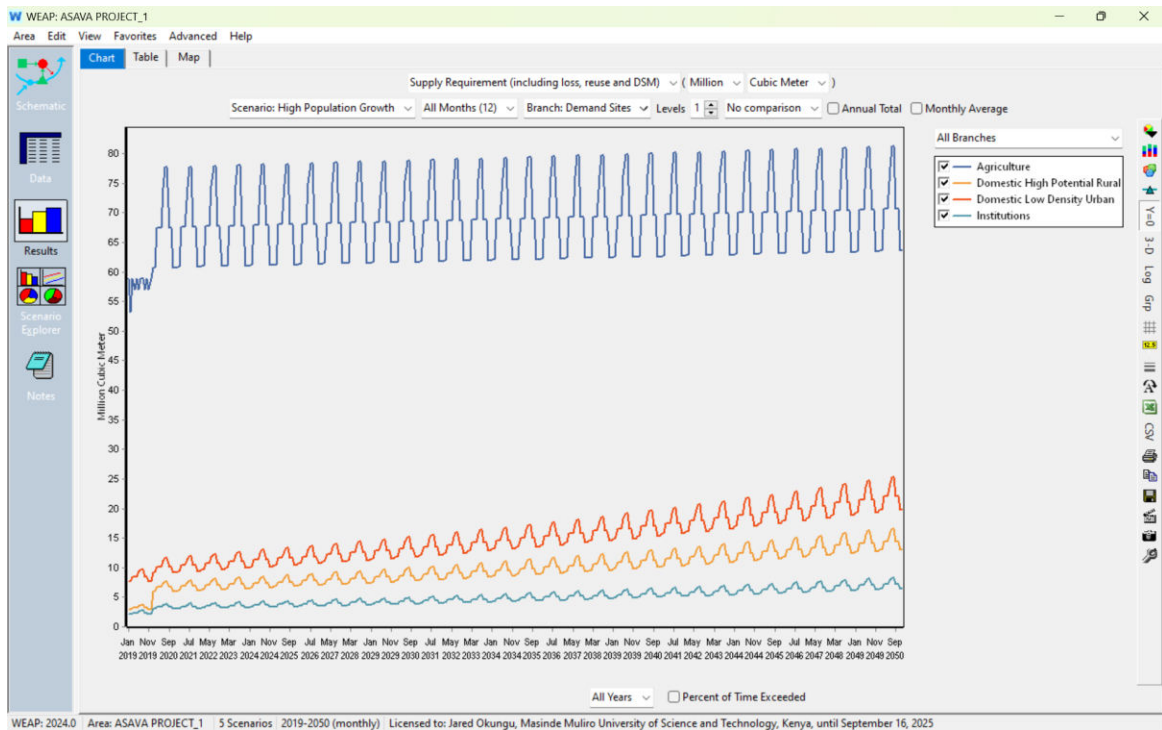
**Wet Climate Sequence:** Projected water requirements decrease to about 35 million cubic meters by 2050, indicating that wetter conditions could alleviate some scarcity issues. However, reliance on this scenario is risky due to climate variability.

The data from the Kipkaren River underscores the urgent need for strategic water management. The projected increases in water demand across various scenarios support the

assertions made by the International Water Management Institute (2021) regarding the critical challenges posed by water scarcity and the necessity for sustainable agricultural practices. This highlights the importance of adaptive strategies tailored to specific environmental and socio-economic conditions, as emphasized by Mehboob *et al.* (2020) in their work on modeling water supply and demand. Policymakers, agricultural planners, and community leaders must collaborate to develop comprehensive water resource management plans that consider factors such as population growth and climate change. Huber-Lee *et al.* (2020) further advocate for an integrated approach to planning that accounts for the interplay between water and energy systems. By taking proactive measures, the Kipkaren River can navigate the challenges ahead, ensuring a sustainable and resilient water supply for its residents and ecosystems.

#### **4.5.1 Allocable Water (Supply Requirement) for Demand Sites (2020-2050)**

The Allocable Water (Supply Requirement) data for the Kipkaren River provides a comprehensive overview of water demand trends from 2020 to 2050 across four primary categories: agriculture, domestic high potential rural, domestic low-density urban, and institutions (Figure 4.20).



**Figure 4.20: Allocable Water (Supply Requirement) for Demand Sites (2020-2050)**

*Source: Researcher (2024)*

The data in figure 4.21 presents water management scenarios across a year, showing consistent inflows of about 29.7 million cubic meters. Outflows are slightly lower but generally balanced with inflows. Supply requirements vary, peaking under high population growth, indicating increased pressure on resources. Unmet demand is minimal in most scenarios, with some deficits during extended dry conditions and high population growth, highlighting the need for adaptive water management strategies to address varying demands and climate impacts.



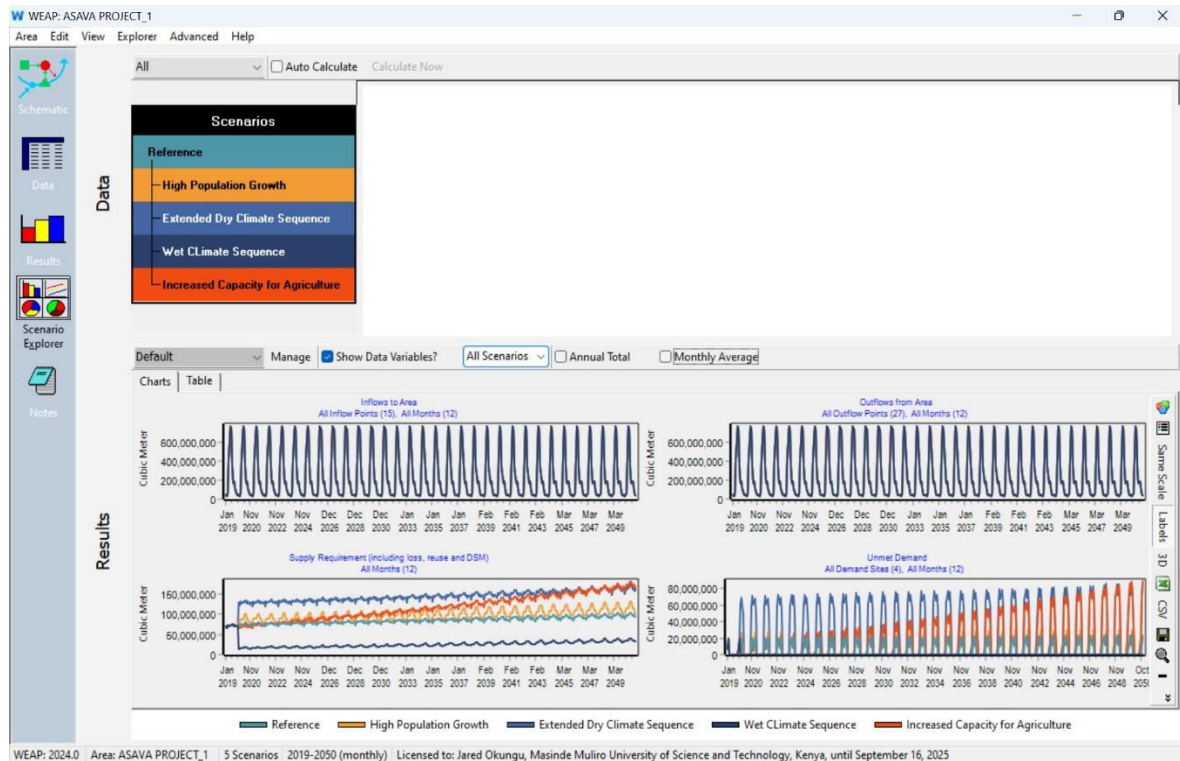
**Figure 4.21: Scenario Explorer illustration of Monthly Average Across all Scenarios (2020-2050)**

*Source: Researcher (2024)*

Starting with agriculture, this category represents the largest share of water demand, beginning at approximately 58.9 million m<sup>3</sup> in January 2019 and projected to increase to around 70.6 million m<sup>3</sup> by January 2050. These findings support Kumar and Bassi's (2021) assertion regarding the potential expansion of agricultural practices and the critical role agriculture plays in the local economy and water use.

As exhibited in figure 4.22, inflows are consistently constant, while outflows show slight fluctuations but remain close to inflow values. Supply requirements increase over time, especially in scenarios related to dry climates and high population growth, reflecting rising

demand. There is no unmet demand reported in any scenario, indicating a balanced system. To improve analysis, consider adding variability in inflows and outflows to better capture scenario differences and potential impacts of changing conditions.



**Figure 4.22: Scenario Explorer illustration of Annual Average Across all Scenarios (2020-2050)**

In the domestic high-potential rural category, demand starts at about 2.9 million m<sup>3</sup> in early 2019 and rises significantly to approximately 14.5 million m<sup>3</sup> by 2050. This growth likely reflects increasing population densities and improved access to water resources in rural areas, indicating a shift toward better infrastructure and higher living standards, a trend echoed by Njora and Yilmaz (2021).

The domestic low-density urban demand also shows substantial growth over the years, highlighting the pressures of urbanization and the rising water needs associated with expanding urban populations. This pattern necessitates careful planning and investment to

address the intensifying demand, as emphasized in Leong and Lai's (2017) study on integrated water resources management.

The institutions category, while smaller in scale, still exhibits steady growth, climbing from around 2.1 million m<sup>3</sup> to about 7.2 million m<sup>3</sup> by the end of the time series. This increase indicates a rising need for water in public services and facilities, further contributing to overall demand in the River.

When analyzing total water demand across all categories, it becomes evident that the cumulative demand rises sharply from approximately 71.5 million m<sup>3</sup> in January 2019 to around 114.3 million m<sup>3</sup> by January 2050. This substantial increase emphasizes the urgent need for effective water resource management to ensure sustainable supply amidst growing consumption.

The implications of these findings are significant. The rising demand, particularly in agriculture and urban areas, underscores the importance of strategic water resource management. Stakeholders will need to prioritize infrastructure improvements, conservation practices, and sustainable water use to effectively address the escalating needs of both agricultural and urban populations. Without proactive measures, as noted by Reznik *et al.* (2022), the River may face challenges in meeting future water demands, ultimately impacting both livelihoods and environmental health.

## **CHAPTER FIVE**

### **SUMMARY, CONCLUSIONS AND RECOMMENDATIONS.**

#### **5.1 Introduction**

This chapter presents a comprehensive synthesis of the findings from the study on water supply and demand simulation in the Kipkaren River within the Upper Nzoia Catchment. Building on the main objective of assessing current water availability and demand, as well as simulating various scenarios and determining optimal water allocation through the WEAP Model, this chapter articulates the key insights gained throughout the research. It highlights the implications of water resource variability on the local ecosystem and community needs, culminating in informed conclusions and actionable recommendations. These insights aim to guide policymakers, practitioners, and researchers in enhancing water management strategies, ensuring sustainable water use, and addressing the pressing challenges faced in the catchment area.

#### **5.2 Summary of Results**

##### **5.2.1 Water Availability in Kipkaren River (1959 - 2019)**

The assessment of water availability in the Kipkaren River within the Upper Nzoia Catchment highlights significant fluctuations in annual headflow from 2019 to 2050. The maximum flow recorded was 554.87 cubic meters per second (CMS) in 2024, while minimum flows dropped as low as 6.35 CMS. Monthly data reveals seasonal variability, with peak flows occurring in October (17.89 CMS) and lower flows during the summer months, particularly in July and August (6.38 CMS and 7.32 CMS, respectively). In 2019, the domestic water demand for the region was approximately 9,796 cubic meters per day ( $\text{m}^3/\text{day}$ ) for a population of 287,000, with urban areas showing higher demand. Institutional

sectors contributed an additional 983.4 m<sup>3</sup>/day, primarily for educational and health facilities, while agricultural demands, especially for irrigation, were about 100,200 m<sup>3</sup>/day. Overall, total demand in the region significantly exceeds average availability during drier periods, underscoring critical challenges in water resource management.

### **5.2.2 Scenario Analysis for different possible water uses in Kipkaren River (2020-2050)**

Using the WEAP model, the simulation of water supply and demand in the Kipkaren River catchment revealed varying water demand across different scenarios from 2020 to 2050. The Extended Dry Climate Sequence indicated a steady increase in demand due to prolonged drought conditions, while the High Population Growth scenario projected a marked rise in demand associated with an expanding population, raising concerns about unsustainable water withdrawal. The Increased Capacity for Agriculture scenario presented mixed outcomes; although improved practices could alleviate some demand pressures, inefficient methods might worsen the situation. The Reference Scenario provided a stable benchmark for sustainable management, whereas the Wet Climate Sequence illustrated fluctuating demand patterns that necessitate careful adaptive strategies.

### **5.2.3 Water Allocation for Demand Sites in Kipkaren River (2020-2050)**

The simulations indicated significant variations in water requirements across scenarios from 2020 to 2050. The Extended Dry Climate Sequence projected a dramatic increase in demand, escalating from 71 million cubic meters in 2019 to approximately 163 million by 2050. In contrast, the High Population Growth scenario anticipated a more moderate increase to about 114 million cubic meters. The Increased Capacity for Agriculture scenario demonstrated the highest demand, peaking at around 170 million cubic meters, underscoring the critical link between agricultural practices and water use. The Reference Scenario served as a baseline, while the Wet Climate Sequence suggested a potential reduction in demand to about 35

million cubic meters, highlighting the impact of climate variability on water availability. Overall, agricultural demand, the largest component, is projected to rise from approximately 58.9 million m<sup>3</sup> to around 70.6 million m<sup>3</sup>. Domestic water needs in high-potential rural areas are expected to increase from about 2.9 million m<sup>3</sup> to approximately 14.5 million m<sup>3</sup>, while low-density urban demands will also see substantial growth. Institutional water requirements, though smaller, are anticipated to rise from around 2.1 million m<sup>3</sup> to approximately 7.2 million m<sup>3</sup>. Cumulatively, total water demand is projected to grow from about 71.5 million m<sup>3</sup> in early 2019 to approximately 114.3 million m<sup>3</sup> by 2050.

### **5.3 Conclusions**

#### **Water Availability:**

The analysis highlights pronounced variability in water availability within the Kipkaren River , significantly influenced by seasonal and climatic factors. The substantial discrepancies between peak and low flows, coupled with high demand from domestic, institutional, and agricultural sectors, suggest that the region is at risk of water shortages, particularly during dry months. These findings underscore the urgent need for adaptive water management strategies that effectively balance supply and demand, ensuring sustainable water resources for all community sectors while addressing the challenges posed by drought and flooding.

#### **Scenario Analysis:**

The findings emphasize the critical need for effective water resource management in the Kipkaren River River, particularly given the diverse impacts of climate and demographic changes on water demand. Each scenario presents unique challenges that could significantly affect the river's water supply and overall ecosystem health. The anticipated increase in

demand, especially under the Extended Dry Climate and High Population Growth scenarios, raises significant concerns about the sustainability of water resources. Additionally, the fluctuating patterns observed in the Wet Climate Sequence highlight the necessity for adaptable management approaches to prevent over-extraction and ecological degradation.

### **Water Allocation:**

The results from the WEAP Model simulations illustrate the complexities involved in managing water resources in the Kipkaren River catchment. Projected increases in water demand, especially under scenarios of prolonged drought and agricultural expansion, indicate an urgent need for robust water management strategies. While wet conditions may offer temporary relief, the overarching trend reveals escalating pressures on water resources driven by environmental changes and population growth. Therefore, optimizing water allocation within the catchment is crucial to ensure a sustainable water supply and mitigate the risks associated with climate variability. These findings reinforce the necessity for effective water management strategies that account for projected increases in agricultural, domestic, and institutional water demands, as the current water supply may prove insufficient to meet future needs. Understanding regional water dynamics and optimizing allocation is vital for sustainable usage and to prevent potential conflicts over limited water resources.

## **5.4 Recommendations**

### **5.4.1 Recommendations for Policy and Practices**

To strengthen water resource management in the Kipkaren River Basin, this study recommends the implementation of Integrated Water Resources Management (IWRM) approaches tailored to the catchment's hydrological variability and demand projections. Key findings from the WEAP model highlight pronounced seasonal water deficits during low-

flow months (e.g., December–February), underscoring the urgency for proactive and adaptive strategies.

First, agricultural water efficiency should be prioritized through targeted policy incentives that promote water-saving technologies (e.g., drip irrigation) and enforce sustainable abstraction limits, particularly during peak demand periods. Policy formulation should be aligned with sectoral targets under the National Irrigation Policy and Vision 2030.

Second, infrastructure investments - including off-river storage reservoirs and household-scale rainwater harvesting systems - are vital for buffering seasonal shortages. These interventions are particularly critical given projected demand increases from domestic, agricultural, and industrial sectors under the Reference and High Growth scenarios modeled in this study.

Third, community-centered awareness campaigns should be scaled up to promote water stewardship. These should focus on behavioral change, equitable water allocation, and uptake of conservation practices at household, institutional, and farm levels.

Fourth, there is a need for institutionalized monitoring and demand forecasting, using tools like WEAP and census-aligned projections to support evidence-based planning. Routine hydrological and socio-economic assessments will enable timely adjustments to allocation frameworks and ensure adaptive capacity.

Lastly, fostering multi-stakeholder coordination - including county governments, WRUAs, agricultural extension bodies, and community-based organizations - will enable localized co-management models that reflect both water security and development priorities. Such collaboration should be embedded within the existing framework of the Catchment Management Strategy (CMS) and County Integrated Development Plans (CIDPs).

## 5.4.2 Recommendations on Objectives

### **Determining Current Water Availability and Demand**

While this objective was achieved through extensive data analysis and model calibration, the study recommends that future assessments maintain continuity by incorporating real-time data streams and remote sensing technologies. Integrating high-resolution climate and land use datasets would enhance spatial and temporal granularity, especially in poorly gauged sub-catchments. This would support the transition from static assessments to dynamic monitoring systems.

**Simulating Scenario Implications Using the WEAP Model** The successful application of WEAP for scenario analysis highlights its value in long-term planning. It is recommended that WEAP be institutionalized as a scenario-testing platform within county and basin-level planning frameworks. Future simulations should include socio-economic shocks (e.g., droughts, policy shifts, migration) and explore hybrid scenario architectures that combine infrastructure expansion, behavioral change, and climate adaptation pathways.

**Determining Optimal Water Allocation Using WEAP** The study confirms WEAP's capability in identifying supply–demand mismatches and testing allocation strategies under constrained conditions. Moving forward, it is recommended that the model be used to inform rule-based allocation schemes that balance equity and efficiency, particularly during low-flow periods. These schemes should be embedded in formal planning tools such as County Water Sector Investment Plans and WRUA Sub-Catchment Management Plans, supported by ongoing stakeholder engagement and validation exercises.

## **5.5 The Study's Contributions to the Body of Knowledge**

This study offers a substantive contribution to the field of water resource management by applying an integrated simulation framework to the Kipkaren River Sub-Catchment—an area previously underrepresented in hydrological scenario modeling literature. Through calibrated WEAP simulations, the study quantified seasonal water availability trends and identified sector-specific stress points, offering empirical evidence of the catchment's sensitivity to both climatic and demographic pressures.

The incorporation of national policy baselines—such as Kenya Vision 2030, the National Water Master Plan 2030, and county-level development trajectories—within the scenario architecture represents a novel methodological alignment between simulation and real-world planning frameworks. This approach enables stakeholders to assess trade-offs between growth-oriented development and water security under constrained hydrological conditions.

Notably, the results from the Reference and High Growth scenarios suggest that without targeted infrastructure and policy interventions, the basin may experience severe allocation deficits during dry months—particularly for agricultural and environmental uses. These outcomes underscore the potential of WEAP not only as a diagnostic tool but also as a predictive platform for designing adaptive allocation strategies tailored to varying demand intensities.

The study fills a critical methodological gap and contributes to evolving discourse on demand-responsive, climate-resilient water planning. Its findings provide a decision-support foundation for planners, researchers, and basin authorities seeking to operationalize Integrated Water Resources Management (IWRM) principles under changing conditions.

## 5.6 Suggestions for Further Research

Building on the insights and limitations of this study, the following research areas are recommended to deepen and operationalize water resource planning in the Kipkaren Sub-Catchment and comparable basins:

Future studies should explore the integration of high-resolution spatial and temporal datasets (e.g., satellite-derived rainfall and evapotranspiration) into WEAP or similar hydrological models. This could improve simulation fidelity, particularly in poorly gauged areas, and support real-time water availability assessments.

Expanding scenario formulation to include participatory design with WRUAs, county planners, and community representatives would improve alignment between model assumptions and on-the-ground realities. Such engagement could enrich scenario narratives with social, institutional, and behavioral drivers often overlooked in technical modeling.

Further research should integrate downscaled climate projections and vulnerability indices to evaluate the robustness of current water allocation strategies under extreme weather events. This could involve coupling WEAP with climate risk frameworks or adaptive planning tools to assess the resilience of infrastructure and policies under future climate conditions.

Longitudinal studies are suggested to monitor how model-supported planning influences institutional decision-making, resource allocation behavior, and water conflict dynamics. This would help evaluate the practical uptake and impact of modeling tools such as WEAP in decentralized governance settings.

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**APPENDICES**

**APPENDIX I: LETTER OF INTRODUCTION**

**From:**

**Eng. Aida Timothy Asava**

**School of Engineering and the Built Environment.**

**Masinde Muliro University of Science and Technology,**

**Reg. No: WRE/G/01-70239/2020**

**Phone No: 0729900871**

**To: .....**

**Date:.....**

Dear Participant,

**RE: RESEARCH PERMISSIONS AND COOPERATION**

I am a M.Sc student at the School of Engineering and the Built Environment, Masinde Muliro University of Science and Technology. I wish to conduct an academic research study on the *“Simulation of Water Supply and Demand in Kipkaren River Sub-Catchment of Upper Nzoia Catchment”*. This research is to be carried out in the Lugari Sub-County, Kakamega County. Data is to be obtained from relevant Government Agencies.

I kindly request your permission to access necessary hydrological, water quality and population data to help me with the research study. I hope that this study shall be helpful in water allocation for various demand scenarios within the catchment. Your participation will be treated with the utmost confidentiality.

Yours faithfully,

Sign.....

**Eng. Timothy Asava**

**M.Sc Student, Masinde Muliro University of Science and Technology**

## APPENDIX II: RESEARCH TOOLS

### (A) RIVER GAUGE TIME SERIES DATA TABLE

Date	Time	Gauge Station ID	Location	River Flow (m <sup>3</sup> /s)	Water Level (m)	Rainfall (mm)	Notes
YYYY-MM-DD	HH:MM	GS001	Kipkaren Bridge	X.XX	X.XX	X.XX	[Any observations or anomalies]
YYYY-MM-DD	HH:MM	GS002	Sosiani Junction	X.XX	X.XX	X.XX	[Any observations or anomalies]
YYYY-MM-DD	HH:MM	GS003	[Other Location]	X.XX	X.XX	X.XX	[Any observations or anomalies]

**(B) POPULATION DATA TABLE**

<b>Parameter</b>	<b>Location 1</b>	<b>Location 2</b>	<b>Location 3</b>
<b>Date</b>	YYYY-MM-DD	YYYY-MM-DD	YYYY-MM-DD
<b>Time</b>	HH:MM	HH:MM	HH:MM
<b>Location</b>	[Location Name]	[Location Name]	[Location Name]
<b>Population Count</b>	X,XXX	X,XXX	X,XXX
<b>Population Density</b>	X.XX people/km <sup>2</sup>	X.XX people/km <sup>2</sup>	X.XX people/km <sup>2</sup>
<b>Age Distribution</b>	[Age Group Data]	[Age Group Data]	[Age Group Data]
<b>Gender Distribution</b>	[Gender Data]	[Gender Data]	[Gender Data]
<b>Household Size</b>	X.XX	X.XX	X.XX
<b>Growth Rate (%)</b>	X.XX	X.XX	X.XX
<b>Migration Rate (%)</b>	X.XX	X.XX	X.XX
<b>Notes</b>	[Notes]	[Notes]	[Notes]

**(C) EXISTING WATER DEMAND FACILITIES DATA TABLE**

<b>Parameter</b>	<b>Facility 1</b>	<b>Facility 2</b>	<b>Facility 3</b>
<b>Facility ID</b>	F001	F002	F003
<b>Facility Name</b>	Facility A	Facility B	Facility C
<b>Location</b>	Location A	Location B	Location C
<b>Type of Facility</b>	Water Treatment Plant	Pumping Station	Reservoir
<b>Capacity (m<sup>3</sup>/day)</b>	X,XXX	X,XXX	X,XXX
<b>Current Usage (m<sup>3</sup>/day)</b>	X,XXX	X,XXX	X,XXX
<b>Service Area</b>	Area A	Area B	Area C
<b>Source of Water</b>	River X	Well Y	Reservoir Z
<b>Operational Status</b>	Operational	Non-operational	Operational
<b>Last Maintenance Date</b>	YYYY-MM-DD	YYYY-MM-DD	YYYY-MM-DD
<b>Notes</b>	[Any observations or issues]	[Any observations or issues]	[Any observations or issues]

**Notes:**

- **Facility ID:** A unique identifier for each facility.
- **Facility Name:** The name of the facility.
- **Location:** The specific location or address of the facility.
- **Type of Facility:** The type of facility (e.g., Water Treatment Plant, Pumping Station, Reservoir).
- **Capacity (m<sup>3</sup>/day):** The maximum water capacity of the facility, measured in cubic meters per day.
- **Current Usage (m<sup>3</sup>/day):** The amount of water currently being used or processed by the facility, measured in cubic meters per day.
- **Service Area:** The geographical area or population served by the facility.
- **Source of Water:** The primary source of water for the facility (e.g., River, Well, Reservoir).
- **Operational Status:** The current operational status of the facility (e.g., Operational, Non-operational, Under Maintenance).
- **Last Maintenance Date:** The date of the last maintenance or inspection performed on the facility.
- **Notes:** Any additional observations or issues related to the facility, such as operational challenges, upcoming upgrades, or other relevant information.

**(D) DEMAND CALCULATION DATA TABLE**

<b>Parameter</b>	<b>Location 1</b>	<b>Location 2</b>	<b>Location 3</b>
<b>Date</b>	YYYY-MM-DD	YYYY-MM-DD	YYYY-MM-DD
<b>Time</b>	HH:MM	HH:MM	HH:MM
<b>Location</b>	[Location Name]	[Location Name]	[Location Name]
<b>Population Count</b>	X,XXX	X,XXX	X,XXX
<b>Water Demand per Capita (L/day)</b>	X.XX	X.XX	X.XX
<b>Total Water Demand (m<sup>3</sup>/day)</b>	X.XX	X.XX	X.XX
<b>Agricultural Demand (m<sup>3</sup>/day)</b>	X.XX	X.XX	X.XX
<b>Industrial Demand (m<sup>3</sup>/day)</b>	X.XX	X.XX	X.XX
<b>Domestic Demand (m<sup>3</sup>/day)</b>	X.XX	X.XX	X.XX
<b>Livestock Demand (m<sup>3</sup>/day)</b>	X.XX	X.XX	X.XX
<b>Seasonal Variation (%)</b>	X.XX	X.XX	X.XX
<b>Peak Demand (m<sup>3</sup>/day)</b>	X.XX	X.XX	X.XX
<b>Off-Peak Demand (m<sup>3</sup>/day)</b>	X.XX	X.XX	X.XX
<b>Notes</b>	[Notes]	[Notes]	[Notes]

**(E) WEAP CALIBRATION AND VALIDATION DATA TABLE**

<b>Parameter</b>	<b>Calibration Period</b>	<b>Validation Period</b>	<b>Description</b>
<b>Date</b>	YYYY-MM-DD	YYYY-MM-DD	The date of the data collection
<b>Time</b>	HH:MM	HH:MM	The time of the data collection
<b>Gauge Station ID</b>	GS001	GS001	Unique identifier for the gauge station
<b>Observed Flow (m<sup>3</sup>/s)</b>	X.XX	X.XX	Measured river flow in cubic meters per second
<b>Simulated Flow (m<sup>3</sup>/s)</b>	X.XX	X.XX	Model-predicted river flow in cubic meters per second
<b>Observed Water Level (m)</b>	X.XX	X.XX	Measured water level in meters
<b>Simulated Water Level (m)</b>	X.XX	X.XX	Model-predicted water level in meters
<b>Nash-Sutcliffe Efficiency (NSE)</b>	X.XX	X.XX	Performance metric for model accuracy (0 to 1)
<b>Mean Absolute Error (MAE)</b>	X.XX	X.XX	Average absolute difference between observed and simulated values
<b>Root Mean Square Error (RMSE)</b>	X.XX	X.XX	Square root of the mean of the squared differences
<b>Calibration Period</b>	Start Date - End Date	Start Date - End Date	Time frame for calibration data
<b>Validation Period</b>	Start Date - End Date	Start Date - End Date	Time frame for validation data
<b>Parameter Adjustments</b>	[Details]	[Details]	Adjustments made to model parameters during calibration
<b>Model Configuration</b>	[Details]	[Details]	Configuration details of the WEAP model
<b>Simulation Scenarios</b>	[Scenario Details]	[Scenario Details]	Specific scenarios used during calibration/validation

## APPENDIX III: WEAP DATA EXPRESSIONS REPORT

Area: ASAVA PROJECT\_1  
 Current Accounts  
 Date: 10/7/2024

```

Key Assumptions
  Domestic Water Use          (m^3)          300
  Agriculture Water Use       (ha)          4000
  Institutional Water Use     (Prod.)       500
  Domestic Variation          MonthlyValues(
Jan, 0.9, Feb, 0.9, Mar, 1, Apr, 1, May, 1, Jun, 1.1, Jul, 1.15, Aug, 1.15, Sep, 1,
Oct, 1, Nov, 0.9, Dec, 0.9 )
  Growth Rate                 (%)          2.51
  Lumakanda                   (%)          2.51
  Institutions                 (%)          1.2
  Agriculture                  (%)          0.2
  TurboDomestic               (%)          2.8
  KipkarenDomestic            (%)          2.27
  Other areas                  (%)          2.27
  Lwandeti                    (%)          2.270

Demand Sites
  Domestic Low Density Urban  Water Use      Annual Activity Level (cap)
GrowthFrom(2.51%,2019,168800)
  Monthly Variation (% share)

Key\Domestic Variation*100/12
  Consumption (%)
20
  Priority                     Demand Priority
3
  Advanced                     Method
Specify yearly demand and monthly variation
  Kipkaren                    Annual Activity Level (% saturation of cap) 75
  Annual Water Use Rate (m^3/cap) 300
  Turbo                        Annual Activity Level (% saturation of cap) 65
  Annual Water Use Rate (m^3/cap) 300
  Lumakanda                    Annual Activity Level (% saturation of cap) 60
  Annual Water Use Rate (m^3/cap) 300
  Institutions                 Water Use      Annual Activity Level (m^3)
GrowthFrom(2.51%,2019,46800)
  Monthly Variation (% share)

Key\Domestic Variation*100/12
  Consumption (%)
35
  Loss and Reuse              Loss Rate (%)
3
  Advanced                     Method
Specify yearly demand and monthly variation
  Health facilities           Annual Activity Level (% saturation of m^3) 80
  Annual Water Use Rate (m^3/m^3) 400
  Industrial Inst             Annual Activity Level (% saturation of m^3) 65
  Annual Water Use Rate (m^3/m^3) 200
  Others                      Annual Activity Level (% saturation of m^3) 69
  Annual Water Use Rate (m^3/m^3) 200
  Agriculture                 Water Use      Annual Activity Level (ha)
GrowthFrom(0.2%,2019,227000)
  Consumption (%)
25
  Priority                     Demand Priority
3
  Advanced                     Method
Specify yearly demand and monthly variation
  Irrigation                  Annual Activity Level (% saturation of ha) 90
  Annual Water Use Rate (m^3/ha) 2000
  Livestock                   Annual Activity Level (% saturation of ha) 55
  Annual Water Use Rate (m^3/ha) 1000
  Learning Institutions       Annual Activity Level (% saturation of ha) 88
  Annual Water Use Rate (m^3/ha) 800
  Domestic High Potential Rural Water Use      Annual Activity Level (cap)
GrowthFrom(2.51%,2019,78200)
  Monthly Variation (% share)

Key\Domestic Variation*100/12
  
```

Consumption (%)

25

Priority Demand Priority

3

Advanced Method

Specify yearly demand and monthly variation

Lwandeti Annual Activity Level (% saturation of cap) 80  
Annual Water Use Rate (m<sup>3</sup>/cap) 300

Other areas Annual Activity Level (% saturation of cap) 85  
Annual Water Use Rate (m<sup>3</sup>/cap) 300

Hydrology

Water Year Method Current Accounts Normal  
Read from File Read from File Not Specified

Supply and Resources

River

River Kipkaren Inflows and Outflows Headflow (CMS)  
MonthlyValues( Jan, 12, Feb, 7, Mar, 11, Apr, 107, May, 177, Jun, 136, Jul, 65, Aug, 32, Sep, 38, Oct, 18, Nov, 9, Dec, 7 )  
Water Quality Model Water Quality?

No

Reaches

Below River Kipkaren Headflow  
Below River Sosiani Inflow  
Below Withdrawal Node 2  
Below Agriculture Return  
Below Withdrawal Node 3  
Below Lumakanda Return  
Below Withdrawal Node 4  
Below Kipkaren Return  
Below Withdrawal Node 6  
Below Domestic High Potential Rural Return

Streamflow Gauges

ICE01\_RGS

River Chepkoilel Inflows and Outflows Headflow (CMS)  
MonthlyValues( Jan, 3, Feb, 3, Mar, 5.1, Apr, 28.8, May, 45, Jun, 67, Jul, 34, Aug, 16.9, Sep, 16, Oct, 10, Nov, 4, Dec, 3 )  
Water Quality Model Water Quality?

No

Reaches

Below River Chepkoilel Headflow

River Sosiani Inflows and Outflows Headflow (CMS)  
MonthlyValues( Jan, 4.2, Feb, 3.8, Mar, 6.6, Apr, 29.11, May, 65, Jun, 79, Jul, 29, Aug, 14.6, Sep, 19, Oct, 12, Nov, 6, Dec, 5 )  
Water Quality Model Water Quality?

No

Reaches

Below River Sosiani Headflow  
Below River Chepkoilel Inflow  
Below Tributary Inflow 1

Local Reservoirs

Musembe dam

Transmission Links

to Domestic Low Density Urban  
from Withdrawal Node 4  
to Institutions  
from Withdrawal Node 3  
to Agriculture  
from Withdrawal Node 2  
to Domestic High Potential Rural  
from Withdrawal Node 6

Return Flows

from Domestic Low Density Urban  
to Kipkaren Return  
from Institutions  
to Lumakanda Return  
from Agriculture  
to Agriculture Return  
from Domestic High Potential Rural  
to Domestic High Potential Rural Return

Other Assumptions

## APPENDIX IIV: APPROVAL BY MMUST - DPS



### MASINDE MULIRO UNIVERSITY OF SCIENCE AND TECHNOLOGY (MMUST)

Tel: 056-30870  
Fax: 056-30153  
E-mail: [directordps@mmust.ac.ke](mailto:directordps@mmust.ac.ke)  
Website: [www.mmust.ac.ke](http://www.mmust.ac.ke)

P.O Box 190  
Kakamega – 50100  
Kenya

#### Directorate of Postgraduate Studies

Ref: MMU/COR: 509099

19<sup>th</sup> February 2024

Aida Timothy Asava  
WRE/G/01-70239/2020  
P.O. Box 190-50100,  
**KAKAMEGA.**

Dear Mr. Asava

#### RE: APPROVAL OF PROPOSAL

I am pleased to inform you that the Directorate of Postgraduate Studies has considered and approved your Masters' proposal entitled: *'Simulation of Water Supply and Demand Dynamics at Musembe Reservoir in River Nzoia Catchment'* and appointed the following as supervisors:

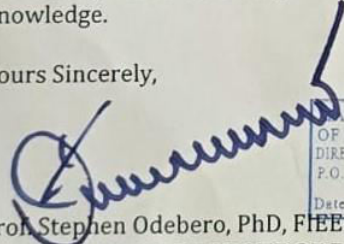
1. Dr. Edwin Kimutai kanda - MMUST
2. Dr. Micah Mukolwe - MMUST

You are required to submit through your supervisor(s) progress reports every three months to the Director Postgraduate Studies. Such reports should be copied to the following: Chairman, School of Engineering Graduate Studies Committee and Chairman, Civil and Structural Engineering Department. Kindly adhere to research ethics consideration in conducting research.

It is the policy and regulations of the University that you observe a deadline of two years from the date of registration to complete your master's thesis. Do not hesitate to consult this office in case of any problem encountered in the course of your work.

We wish you the best in your research and hope the study will make original contribution to knowledge.

Yours Sincerely,

  
Prof. Stephen Odebero, PhD, FIEEP  
DIRECTOR, DIRECTORATE OF POSTGRADUATE STUDIES

MASINDE MULIRO UNIVERSITY  
OF SCIENCE AND TECHNOLOGY  
DIRECTORATE OF POSTGRADUATE STUDIES  
P.O. Box 190 - 50100, KAKAMEGA (K)

Date:.....