Application of SWAT and WEAP Models for Sustainable Management of Water Resources in the Two Rivers Dam Catchment, Uasin Gishu

By

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DECLARATION

Declaration by Candidate

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To the almighty God, for good health, knowledge and intellect to conduct the study, my parents, brother, sister, relatives and friends without whose love and support the completion of this work would not have been possible.

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ABSTRACT

Kaptagat Forest, the main source of Ellegerini River which feeds the Ellegerini Dam and Two Rivers Dam, is under threat of extinction due to human activity. The Two Rivers Dam catchment that has over the years been a source of water in Uasin Gishu County is slowly depleting and urgent measures are required to restore it. Activities including commercial logging, charcoal burning and firewood harvesting have exerted a lot of pressure on the catchment, posing a great threat to the livelihoods of the people of Eldoret town who depend on the reservoirs for water supply. The main objective of this study was to develop SWAT and WEAP models for the sustainable management of water resources in the Two Rivers Dam catchment. The specific objectives were to set up and apply SWAT model to generate simulated river flows draining to the Two Rivers and Ellegerini Reservoirs as an input to the WEAP model, to determine the impact of land use change on the hydrological function of the Two Rivers Dam catchment, to set up, calibrate and validate a WEAP model for the Two Rivers Dam catchment and to apply the WEAP model in analyses of various management and infrastructural development scenarios to enhance water storage in the Two Rivers and Ellegerini Reservoirs. The goodness of fit SWAT model statistical evaluation indices attained during the calibration period of 1980 -1984 were R^2 = 0.854, NSE = 0.822 and Bias = 0.392. Additionally, for the validation period of 1985 -1989 the R^2 = 0.786, NSE = 0.815 and Bias = 0.381. The modeled results indicate that the land use change resulted in decreased baseflow and increased surface runoff hence the high fluctuations of water levels in the Two Rivers and Ellegerini reservoirs. The WEAP model results for actual and simulated water demand in calibration period of 2019, the R^2 = 0.88 while during the validation period in the year 2020, the R^2 = 0.85. The results of model simulation indicated that the management option that had the most impact on all the scenarios was the reduction of unaccounted for water while the one with the least impact was increased water use efficiency. It was concluded that the models were able to simulate the observed conditions reasonably well and can therefore be used to effectively manage water resources and assist the relevant stakeholders in decision-making. The study recommended that forested areas need to be properly conserved in order to restore the hydrological function of the catchment.

ABBREVIATIONS

DEM	Digital Elevation Model
ELDOWAS	Eldoret Water and Sanitation Company
FAO	Food and Agriculture Organization
GIS	Geographical Information Systems
GWP	Global Water Partnership
IWRM	Integrated Water Resources Management
KMD	Kenya Meteorological Department
KSS	Kenya Soil Survey
MAE	Mean Absolute Error
MSE	Mean Square Error
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe Efficiency
OAT	One-At-a-Time
RGS	River Gauging Station
RMSE	Root Mean Square Error
SWAT	Soil and Water Assessment Tool
USDA	United States Department of Agriculture
WEAP	Water Evaluation and Planning System
WRA	Water Resources Authority

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CHAPTER ONE: INTRODUCTION

1.1 Background

Water is a crucial element in the sustenance of life. All life forms require water for survival and also water is essential for economic growth and development. In order to achieve the sustainable development goals (SDGs), developing nations need to improve their water supply and sanitation (Hagan, 2007). The specific SDG addressed in this study is SDG No.6 which is, "To ensure availability and sustainable management of water and sanitation for all".

A catchment is a natural system that is made up of a number of components, these include; water sources (inputs), demands (water use), in-stream and off-stream components, and other intermediates such as treatment and recycling. It is thus appropriate to handle water resource management in an integrated way as a single system. As the Global Water Partnership defines Integrated Water Resources Management (IWRM) as a "process which promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Giordano & Shah, 2014). Water resource management should therefore be implemented in a sustainable manner by encompassing and balancing water needs among all uses including; domestic, industrial, agricultural (irrigation), power generation and ensuring provision for environmental flows for biodiversity and ecosystem services (Tessema, 2011).

The Kenyan government plans to increase the water storage capacity in various catchments through the construction of dams (Akivaga et al., 2010). The Kenya Vision 2030 rightly recognizes that Kenya as water-scarce and therefore under the water and sanitation pillar, the vision is to ensure that sanitation and water services are not only available, but can be accessed sustainably by all Kenyans. Over time it has become more evident that the water problems in the nation cannot be solved by the ministries of water and professionals in water management alone. Therefore, this study can assist in providing solutions related to the management of water.

The Kaptagat Forest is the catchment area for Ellegerini River which feeds the Ellegerini Dam and the Two Rivers Dam. The reservoirs have capacities of 3,450 m^3/day and 14,950 m^3/day respectively. The Ellegerini Dam is located 12 km upstream of the Two Rivers Dam. The water is treated at the Sosiani treatment works which has a capacity of 14,950 m^3/day and Kapsoya treatment works 3,450 m^3/day. Kapsoya treatment works sources its water from the Ellegerini Dam. Eldoret gets additional water from Chebara Dam which delivers 18,000 m^3/day to the town. The total water quantity distributed in Eldoret Town is 36,400 m^3/day (Sum, 2014).

The water reticulation system in Eldoret is inadequate with only 180,000 households (37.8%) connected to the system (Masakha, 2017). Residents of Eldoret can also not rely on ground water in Eldoret because it contains high levels of minerals thereby making use of ground water not viable. Rivatex textile and Raiply wood processing companies for instance, have boreholes with saline waters (Sum, 2014).

The persisting water shortage in Eldoret is as a result of destruction of the Kaptagat forest, which is a key source of water for the water reservoirs supplying water to the town. Catchment degradation of the water tower due to deforestation and conversion of forest area to agricultural land coupled with the rising population in Eldoret town has put a strain on the water resources in the catchment. The SWAT and WEAP models were therefore developed in this study for the sustainable water resources management of the Two Rivers Dam catchment.

1.2 Statement of the Problem

Kaptagat Forest, the source of Ellegerini River which feeds the Ellegerini and Two Rivers Dams, is under threat of extinction due to human activity. The ecosystem that has over the years been a source of water to Eldoret town, is slowly depleting and urgent measures are required to restore it. Activities including commercial logging, charcoal burning and firewood harvesting have exerted a lot of pressure on the catchment, posing a great threat to the livelihoods of the people of Eldoret Town who depend on it for sustenance. Water levels in the Two Rivers and Ellegerini Reservoirs that supply water to Eldoret town continue to recede due to the depletion of forest cover and rising demand for water. The situation has on some occasions become so dire that the Eldoret Water and Sanitation Company (ELDOWAS) announced on the 20th of April of 2019 that the water levels at the Two Rivers and Ellegerini Dams had reached critical levels. The company stated that the dams would be closed down for a few days unless it rained. This necessitated the firm to begin drafting a water rationing plan for Eldoret Town.

According to the Chairman of Eldoret Water and Sanitation Company (ELDOWAS), Mr. Cornelius Chepsoi, there is competition for water as the population of Eldoret Town continues to increase and there is a need to build more reservoirs to address the rising water requirement in the Town. The persisting water shortage in the Two Rivers Dam catchment has compelled ELDOWAS to propose the construction of more dams to alleviate the water crisis. This shows a need to do water management in the catchment.

1.3 Study Objectives

1.3.1 Main Objective

The main objective of this study is to develop SWAT and WEAP models for modelling the sustainable management of water resources in the Two Rivers Dam catchment.

1.3.2 Specific Objectives

1. To set up and apply SWAT model to generate simulated river flows draining to the Two Rivers and Ellegerini Reservoirs as an input to the WEAP model.
2. To determine the impact of land use change on the hydrological function of the Two Rivers Dam catchment.
3. To set up, calibrate and validate a WEAP model for the Two Rivers Dam catchment.
4. To apply the WEAP model in analyses of various management and infrastructural development scenarios to enhance water storage in the Two Rivers and Ellegerini Reservoirs.

1.4 Justification of the Study

A catchment is the smallest complete hydrological unit of analysis. Integrated catchment management is therefore a practical and ideal operational approach for instant and closer monitoring (Höllermann et al., 2010). The persisting water shortage in Eldoret is as a result of destruction of the Two Rivers Dam catchment due to deforestation and the problem is exacerbated by the rapidly growing population in the town. This highlights a need for water management of the catchment.

According to the census report by the Kenya National Bureau of Statistics (KNBS) and the Kenya Population and Housing Census (KPHC) that conducted the population census in 2019, the population of Eldoret town has risen from 289,380 in the year 2009 to 475,716 people in the year 2019. This rapid increase in population without an increase in available water resources indicates a need to conduct this study, as the study will inform the water utility (ELDOWAS) and the other various water stakeholders on proper water management and more efficient water allocation to the various water users in the catchment.

As efforts to meet water demand in Eldoret accelerate, IWRM tools such as WEAP, which was used in this study, will provide opportunities for water utilities in Eldoret Town including ELDOWAS and other stakeholders to develop a comprehensive planning framework for sustainable water resource management.

Land use and land cover dynamics on water resources availability will guide the land use planners to be more effective in the planning of Eldoret Town and the Two Rivers Dam catchment area. The information obtained can also be applied to other urban areas with similar problems.

The rates of land cover changes and their spatial distributions would be important in the management of watersheds which is done by the Water Resource Authority (WRA) which builds the capacity of land owners organized in Water Resources Users Associations (WRUAs) to develop and implement Catchment Management Plans (CMPs).

1.5 Study Area

1.5.1 Geographical Location

The Kaptagat Forest catchment is part of the larger Cherangany Forest Ecosystem, one of Kenya’s five water towers. It is located in Elgeyo Marawket county (Kenya Forest Service, 2014). The forest is located approximately 350 Km North West of

Nairobi and is part of the North Rift Conservancy (Ontumbi et al., 2015). The forest lies at an altitude of 2,456 meters above sea level, within a longitude $35^0$28'30''E and $35^0$32'30''E and latitude $00^0$21'30'' (Kenya Forest Service, 2014). The forest is surrounded by four villages, namely; Chepkorio/Flax, Cheptigit, Chesebet/Kaptagat area, and Masorta (Kemunto, 2016). The forest is bordered to the East by Penon Forest, to the North by Sabor Forest, to the South by Flax sub location and to the West by the Kaptagat Settlement Scheme (Kenya Forest Service, 2014). The forest is accessed through the Eldoret - Eldama Ravine road that crosses the forest close to the junction to Flax trading centre to Chepkorio market (Kenya Forest Service, 2014).

1.5.2 Climate

The Kaptagat forest has a wet and cool climate with an average annual rainfall that ranges from 1200 to 1700 mm and an average temperature range from 14.8 to 28 ^{0}C. The dry period in the forest is from January to March and the wet season from May to July. The short rains occur between October and December (Kenya Forest Service, 2014).

1.5.3 Soils and Geology

Kapatagat lies 10 kilometers to the west of the Elgeyo Escarpment in the highlands of Keiyo Escarpment and is sited on phonolite lavas of the Uasin Gishu plateau. Three major faults lie within the immediate vicinity of Kaptagat. The soils in the catchment are mainly brown loam soils. The soil in the area is deep, with clay-enriched lower horizon (Kemunto, 2016).

1.5.4 Land Use/Land Cover

The Kaptagat forest catchment has an abundant supply of accessible exotic trees including; pine, blue gum eucalyptus and cypress, and indigenous trees (Braitstein, 2014). The indigenous tree species include; Bamboo, *Olea africana, Cyzigium sp. Prunus Africana, Abyssinica sp. Dombeya sp. Achira sp. and Techlea nobilis* (Kemunto, 2016). The forest has other types of vegetation and shrubs with a climber, Periploca linearifolia locally known as ‘‘Sinendet’’ which is considered by the local community to have medicinal value. The forest also has ‘‘Siryat’’ *Rhus natalensis* and *Vernonia auriculifera* locally known as ‘‘Tebengwet’’. The indigenous tree species that is dominant in the forest is ‘*Olea Africana*’, the wild olive (Kenya Forest Service, 2014). The forests has beats that cover a total area of 5543.56 ha where 0.5% of the land is covered by grasslands, 27.5% is occupied by bush land, 42% covered by indigenous trees and 30% covered by plantations (Kemunto, 2016).

The deforestation of the Kaptagat forest water tower has been caused by rampant felling of trees for firewood and timber use and the conversion of the catchment land into agricultural land for wheat production and subsistence farming. There has also been indiscriminate wood harvesting which has been one of the main economic activities for the women in the catchment as they prefer to use wood fuel for cooking (Braitstein, 2014). A majority of the people in the catchment are mixed farmers keeping large herds of cattle and also practicing crop farming (Kemunto, 2016). Charcoal burning is also another economic activity in Kaptagat and is mainly carried out at night. The Kaptagat forest lacks a fence around it and therefore people illegally access the forest to harvest timber because timber trade is a lucrative business in the Two Rivers Dam catchment (Kemunto, 2016). Kaptagat forest has numerous ecotourism sites such as shrines, sites where you can make films, nature trails and caves. The forest also has an Agri-tourism potential with activities including fish pond rearing and bee keeping. The cultural sites in the forest include Kipsao, Chepkermetet, Masorta, Kaptmatabaru and Kabarkeon among others (Kenya Forest Service, 2014).

Kaptagat is within the forest zone of Elgeyo Marakwet County and it is well connected by road and railway. The Kaptagat market centre has grown fast due to rapid urbanization and high levels of development (Uasin Gishu County Dvelopment Plan, 2018).

According to the census report by the Kenya National Bureau of Statistics (KNBS) and the Kenya Population and Housing Census (KPHC) that conducted the population census in 2019, Uasin Gishu County has a population of 1,163,186 consisting of 580,269 males and 582,889 females. The county has 304,943 households and the average household size is estimated to be 3.8. The county's population is distributed over an area of 3,392.20 km^2 and therefore the population density is approximately 343 persons per square kilometer (KNBS Census, 2019).

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Numerous nations in the world currently have challenges in fresh water management which is as a result of rising competition for the scarce natural resource. Due to inadequate finances, the vulnerable and finite nature of water, and its rising demand, it is necessary to utilize the resource with maximum efficiency. Leaders and water managers need modern tools to provide solutions to across various sectors which are often complex and interdependent. Integrated Water Resources Management (IWRM) is a tool developed to address issues where water actions interact with natural and social systems (Grigg, 2019).

The allocation of water is crucial in water resource management. It is essential to develop proper methodologies to allocate water and establish water management policies and institutions as recognized by water planners, governments and researchers (Wang, 2005). In order to solve complex water problems, the design of policies requires an integrated approach. The goal is to get an insight into all aspects of the problems and therefore being able to reach a sustainable decision. The solving of unstructured and complex issues in integrated water resource management is however faced with dispute, controversy, misused and unused knowledge, decline of trust in the decisions of the government among the public and project delays and ultimately project failure. Decision makers and influential people in the water management sector now need computer models because they represent scientific understanding and can therefore use the information from the output of the computer models (Kolkman et al, 2005).

Kenya's total renewable water resources amount to approximately 30.7 billion cubic meters of water per annum while the Kenyan population consumes about 33 billion cubic meters of water per annum which results in a deficit of 2.3 billion cubic meters of water per year (Mulwa et al., 2021). The natural renewable water resources in Kenya rely mainly on fragile and little watersheds covered by forests located in the humid highland areas in the nation. Kenya has only five main water towers including Cherangani Hills, Mt. Kenya, Mt. Elgon, Aberdare Ranges and the Mau Forest Complex which are under the catchment degradation threat. Therefore, catchment conservation is very essential in ensuring the sustainability of Kenya's water resources and provision of sufficient water supply to the country's population.

2.2 Water Management

Water management entails overseeing water resources under a particular set of regulations and policies. The management of water resources entails multiple goals that are often times partly conflicting that aim to improve and maintain the state of water resources. Water allocation should be done among competing uses. The water that is available in many areas is often polluted and is therefore not usable and may require treatment which is very expensive. Rapid industrialization and urbanization in developing nation exacerbates the demand of water. Water was once an abundant resource but is now becoming a very valuable commodity due to its rising demand, overuse and frequent occurrences of drought (Wostl, 2007). The various uses of water including municipal, environmental, agricultural and municipal uses have to be integrated into and coordinated with overall water management. Public health, sustainability, economics and environmental are critical factors. There should be more storage of water in reservoirs and aquifers via artificial recharge which is essential in order to save water during the times its surplus to enable its use during times of water scarcity (Maliehe & Mulungu, 2017).

Sustainable water resources management has over the past decade become a very important issue. Water management problems have to be handled using an integrated approach considering human, environmental technological factors and their interdependence (Li et al., 2015).

2.3 Integrated Water Resources Management

The Global Water Partnership (GWP) defines Integrated Water Resources Management (IWRM) as an "exercise that enhances coordinated management and development of land, water and other related resources, to maximize the resultant social and economic welfare in an equitable fashion without any compromise on the sustainability of crucial ecosystems" (Giordano & Shah, 2014). IWRM is a sustainable outlook on water resource management that entails its multidimensional nature -space, time and multidiscipline (technology/science) and (stakeholders/users/regulators/neighbors/providers/) and the need to embrace, relate and address the dimensions in a holistic manner so as to achieve sustainable solutions (Bonzi et al., 2010).

The space dimension maintains that the basin is the natural unit for all efforts in water management and it is therefore crucial to think in a global perspective before acting locally.

The time dimension recognizes that sustainable development measures developed now should be in line with the long-term interests of the future generations. Sustainable development should therefore meet the needs of the current generation without causing difficulty in the ability of future generations to meet their own needs (Giordano & Shah, 2014).

The multidiscipline dimension demands consideration of several parameters during the decision-making process:

i. Health and legislation issues
ii. Institutional and political issues
iii. Cultural and historical issues
iv. Socio-economic impact
v. Technology and technique
vi. Social, ecological/environmental and economic effects

With regards to the stakeholder dimension, all stakeholders need to be involved in all levels of decision making so as to address all conflicting desires of the various participants involved in the decision making.

There is more to Integrated Water Resource Management (IWRM) than its traditional description of balancing and integrating the demand of water resources. The IWRM concept embodies integration across all sectors, demand integration, environmental integration, use integration as well as user integration needs (Giordano & Shah, 2014).

2.4 The Framework for IWRM Planning

The framework that is the most widely accepted is the “Driving Forces-Pressure-State-Impact-Response model” (DPSIR) framework of IWRM planning. The DPSIR framework is an extension of another framework known as the PSR (Pressure-State-Response) developed in the 1970s by Anthony Friend and later adopted by the OECD’s State of the Environment (SOE) group (Alfarra, 2004).

The general consensus about IWRM at the watershed level is sustainable management of water resources. Therefore, it is crucial to approach the overall watershed and include all elements in the catchment that are influenced by water.

Figure 2.1 shows a schematic view of the elements, which can be stored in the form of GIS database sets.

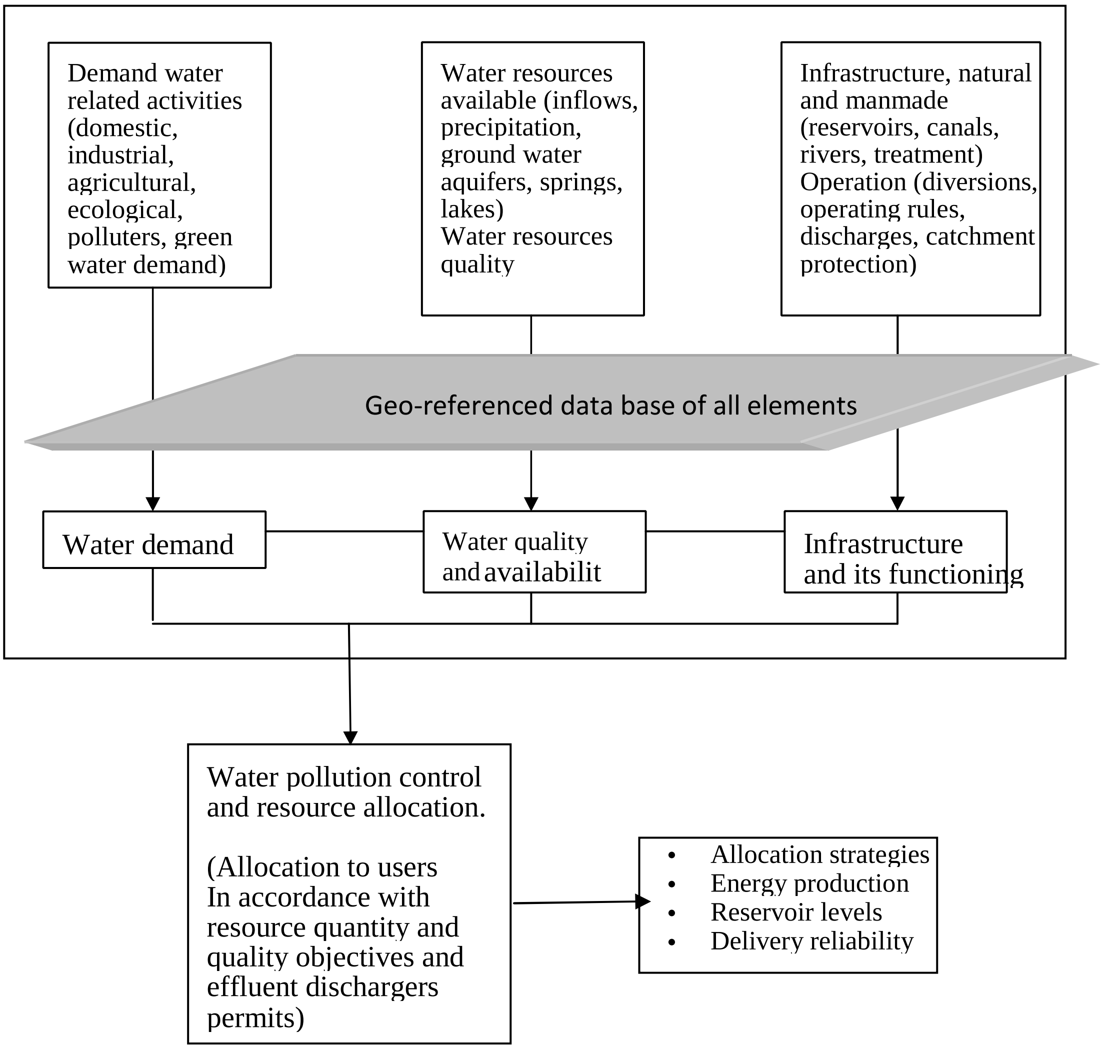


Figure 2.1 Schematic Elements of Water Management, (Kristensen, 2004)

The elements in the above Figure 2.1 can be analytically evaluated using a water management conceptual framework based on the DPSIR model. This therefore, enables a comprehensive evaluation of the issues by examining the relevant pressures and driving forces on the environment, consequent environmental state, its effects, responses undertaken and their linkages between among elements. A general DPSIR water management model is indicated in Figure 2.2.

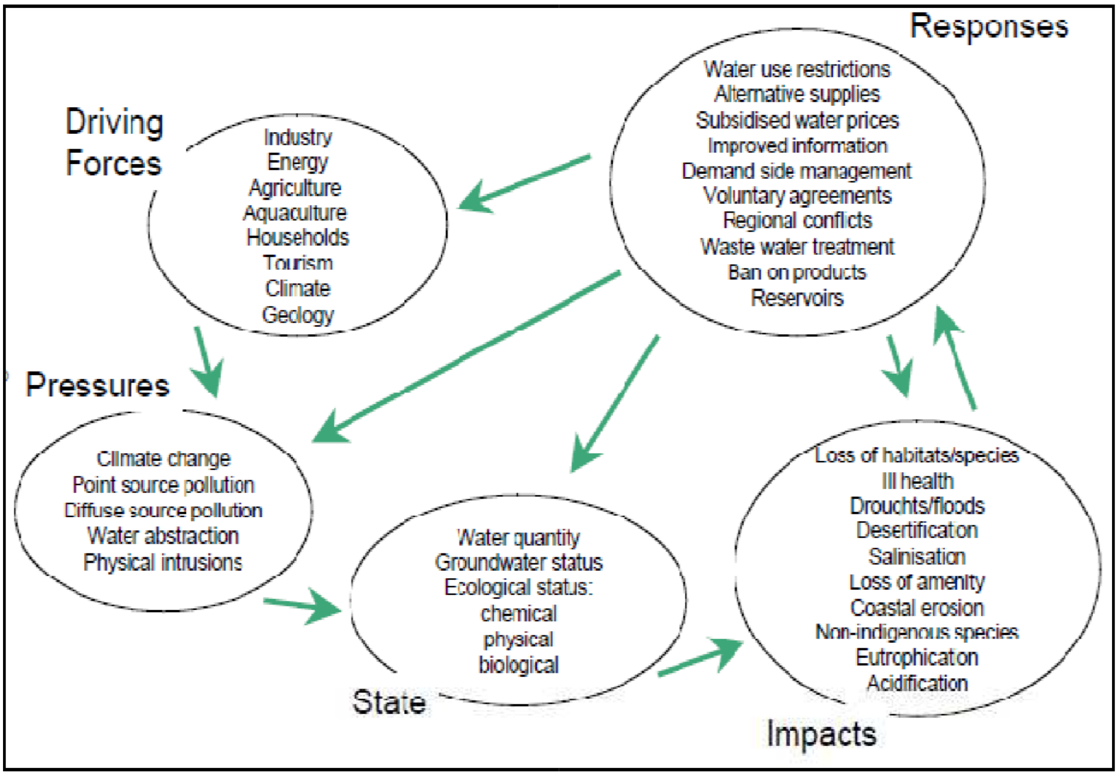


Figure 2.2 DPSIR Model (source: (Kristensen, 2004))

2.5 Land Use Land Cover

Changes in land use and land cover (LULC) are affected by factors including; increase in population, infrastructural development, human ideologies and behavior, development patterns, values and planning (Korir, 2014). Changes in land cover influence numerous catchment processes such as rainfall-runoff and soil erosion. The rainfall-runoff relationships in a river basin are primarily influenced by many facets specifically the interaction of soils, climate and land cover (Ahn et al., 2016).

Land use land cover can result in infiltration capacity changes of the land and hence leads to a change in the runoff dynamics. (Obahoundje et al, 2017). The findings of the study showed that the land use change effect is considered in the scenario, the runoff increased by 2.63%.

The prediction of the land cover change effects in catchment runoff characteristics entails the use of hydrological models. The use of the models entails GIS and remote sensing integration because one of the key input parameters is the curve number (CN) which is estimated from land cover, which is in turn approximated from remotely sensed data including satellite images. The use of the Soil Conservation Service Curve Number (SCS CN) method considers the relations between soil characteristics and land cover thereby making hydrological models suitable for assessment of the effects of changes in land cover (Tasdighi et al., 2018).

The nature and location of change in land cover that has happened in a particular basin can be recognized from remote sensing images and their classification at different time periods thereby producing different categorized maps from which the information about the land cover change can be generated (Tasdighi et al., 2018).

2.6 Water Resource Management Models

The utilization of hydrological models in making decisions enables the water stakeholders to select an optimal course of action. Models enable users to understand and reason within a logical framework on the processes of interest (Hamlat et al., 2013).

Hydrological models are therefore essential tools that enhance the study of hydrological processes. Moreover, they enable investigation on responses to anthropogenic and natural factors. However, due to limitations in representation of intricate natural systems, model calibration and validation must be conducted before the application of such models in order to ensure they properly represent the reality.

The correct approximation of the volume of runoff draining out of basins is a very crucial issue in engineering and hydrology because it forms the basis of design, planning, water supply management, river, irrigation and flood protection works. Hydrological models are therefore important tools in the prediction and forecasting of water quality and quantity for water management stakeholders (Chow, 1988). A model can simply be described as a representation of a physical system or process. Models are simple representations of complex hydrological systems and thus aim to represent and predict the runoff response to rainfall input for a specific catchment.

Challenges in water management are becoming more interconnected with other issues related to development coupled with legal, economic, environmental, social and political factors at both local and national levels and at certain instances both international and regional levels. Numerous water problems have become very complicated, large and interconnected to be able to be solved by a single institution, irrespective of the resources and authority entitled to it, technical management expertise, available capacity and political goodwill.

Various programs are designed to simulate water infrastructural development and management in watersheds. Most of these softwares are based on node-link network representation of the water resources systems in which they simulate. Some of the models include optimization which provide a detailed representation of water operation policies. Most of them contain graphical and menu driven interfaces that enhance interaction with the user. The programs are properly utilized in exercises of shared vision that involve all water stakeholders within a watershed.

The examples of water resources management models include:

i. MIKE Basin
ii. Water Balance Model (WBalMo)
iii. River Basin Simulation Model RIBASIM
iv. MODSIM
v. The Soil & Water Assessment Tool (SWAT)
vi. Water Evaluation and Planning System (WEAP)

MIKE Basin was developed in Denmark by the Danish Hydraulic Institute (DHI) and it addresses reservoir operation, conjunctive use water allocation and water quality issues. The software utilizes hydrological modelling coupled with GIS to provide solutions at the catchment level. The philosophy of the software is model intuitivity and simplicity and yet provide deep insight for management and planning. The MIKE Basin program emphasizes on both visualization and simulation in both spatially and temporally thereby making it critical for creating consensus and understanding.

The Water Balance Model (WBaLMo) is an interactive catchment management and river simulation system developed in Germany by WASY Ltd. The software utilizes Monte Carlo simulation to model precipitation and runoff processes stochastically and also balances their respective time series with monthly changes in reservoir storages and the water use needs. The model is used in the identification of catchment management guidelines for reservoir systems design, river basins and their operating policies and also evaluates the environmental impact for infrastructural development projects.

The River Basin Simulation Model (RIBASIM) is a software used in the analysis of watersheds under varying hydrological conditions. The tool is a flexible and comprehensive tool that links hydrological components spatially with the water users in a particular catchment. The software package was developed in Netherlands by Delft Hydraulics. The software program is user friendly, is based on an integrated framework, is GIS oriented and enables the user to assess various measures related to operations, infrastructural development and demand management based on water quality and water quantity in a river basin.

MODSIM is catchment network flow model and decision support system developed by the Colorado State University. The model was designed to meet the current rising pressures and demands on catchment managers. The graphical user interface of the software package enables users to create any watershed's topology through clicking certain icons and arranging the system objects in a configuration on the display that the user desires. The program's database management system controls the data structures embodies in each object of the model.

2.7 SWAT Model Description

SWAT is a semi-distributed and physically based model which was developed by the United States Department of Agriculture (Pokhrel, 2018). The application of the model is to simulate the hydrology of a basin, growth of crops, nutrient transfer, climate change, water quality, sediment yield and the effects of land management practices (Marhaento et al., 2017). The SWAT model divides a catchment into sub-basins which are in turn further divided into Hydrologic Response Units (HRUs). The HRUs are units with similar soil type, slope and land use (Krysanova & Srinivasan, 2014). The model then calculates each HRU's water balance. Additionally, the SWAT model uses a GIS interface called Arc SWAT which is very user friendly.

Estimation of the SWAT model parameter, the Curve number (CN), is a function of the hydrologic soil group, land cover type and antecedent moisture conditions. To determine the curve number, the land cover and soil type coverages were combined through overlay analysis of GIS. The resulting coverage was used in the delineation of the catchment area into sub areas that have the same land cover and soil type, known as Hydrologic Response Units (HRUs). The representative curve number of each sub catchment was ascertained as the weighted average of all CN values of the sub areas given by the expression [Eqn 2.7]:

$$CN = \frac{\sum_{i=1}^{N} CN_i A_i}{A}$$ ……………………………………………………….….. [Eqn 2.7]

where A_i and CN_i are the area and the curve number of the sub area in each sub catchment i, respectively. The curve number is one of the direct inputs in the SWAT model and was used to compute direct runoff and later peak runoff through the relationships between curve number and runoff depth given in equation 2.8:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)}$$ ……………………………………………….………….. [Eqn 2.8]

Where Q = runoff depth(mm), P = rainfall depth (mm), S = potential maximum retention (mm), I_a = Initial abstraction (mm), which includes short-term losses due to surface detention, interception, infiltration and evaporation. From the study of many catchments, an empirical relation I_a = 0.2S was developed.

By substituting Ia = 0.2S in equation 3.7 becomes

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$ ……………………………………………………...…… [Eqn 2.9]

The potential maximum retention, S, is related to dimensionless Curve Number (CN) as follows

$$S = \frac{25400}{CN} - 254 \qquad \text{[Eqn 2.10]}$$

By varying the curve number according to the land cover, different values of runoff depths and peak runoff values were obtained and used as a measure of the hydrological impacts of land cover and land use changes in the Two Rivers Dam catchment.

2.8 SWAT Model Applications

Bailey (2015) utilized the SWAT model to examine the stream flow hydrology of Sierra Forest catchment which is located in the state of Nevada in the United States of America. The author used the model to simulate stream flow on a daily time step. In the catchment, 72% of the land cover was a dense mixed conifer forest. The model performance of SWAT was reasonably good where the coefficient of determination (R^2) was 0.59 and the Nash-Sutcliffe Efficiency was also 0.59. The model performed well despite the complexity of the hydrology of the watershed. Although, the model performed well, there was still two crucial missing hydrological processes which include; isolated peak flow events and the timing of snowmelt. Additionally, daily time step simulation of stream flow was key in comprehending the functioning of the catchment.

Shi et al (2013) used the SWAT model to model the hydrological processes of the Huaihe river in Xixian basin with an area of area of 10,191 km^2 in China. The inadequacy of water in Huaihe River which is the sixth largest river in the country was as a result of enormous human activity which is exacerbated by climate change in the area especially, Xixian, which is situated in the upper reaches of the river. Xixian's population is over one million and produces more than a billion kilograms of crop annually and is therefore a very crucial county for agriculture in China. The projected population growth and changing climate is expected to further aggravate the water situation thereby endangering agricultural activity in the watershed. The hydrological model was therefore necessary to enable the stakeholders better comprehend the interaction of hydrological processes and land use to ensure sustainability in usage of water. The authors assessed the SWAT model performance in the Xixian catchment where they carried out uncertainty analysis which is uncertainty fitting sequentially, generalized likelihood uncertainty estimation, parameter solution and ultimately conducted model calibration. The results showed that the model performed well in the catchment where the R^2 was 0.74 and NSE was 0.68 and that the analysis of hydrological water balance of the watershed showed that baseflow was a critical aspect affecting the final discharge in the basin and that over sixty percent of the annual rainfall is lost via evapotranspiration. The SWAT calibrated model can further be utilized in evaluating the impact of land use change, climate change and to determine the impact of various water management scenarios and cultivation styles on the catchment's water resources.

Pokhrel (2018) assessed the effect of land use change on the stream flow in Kathmandu's Bagmati river outlet in an area called Khokana in Nepal using the SWAT model. Changes in land use play a major role in altering hydrological response and examining its effects which can assist in developing a pragmatic and sustainable strategy for preservation of a basin. The researcher's objective was to assess the land use change effects on the discharge of Bagmati river at the Khokana river gauging station at the outlet of the Kathmandu valley. The study utilized the SWAT model to evaluate the influence of land use change from the year 2000 to 2010. Moreover, the ParaSol (Parameter Solution) method was used to carry out sensitivity analysis within SWAT Calibration and Uncertainty Procedure (SWAT-CUP). Four statistical parameters which include; Bias, Nash-Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2) and RMSE Observations' Standard Deviation Ratio (RSR) were estimated in the model performance assessment. The results indicated a good agreement between the actual and simulated monthly discharge data as the R^2 was 0.88, NSE was 0.90, RSR was 0.34 and Bias was 0.03. The land use change data indicated that from the year 2000 to 2010 there was a 6% rise in the built up area and a decrease in the remaining areas including, shrub, agricultural land use, grass, open field, forest and area covered by lakes and rivers. The contribution of surface runoff to stream flow experienced a 27% increase. However, the contribution of lateral flow to groundwater and stream flow decreased by twenty five percent.

Mengistu et al. (2019) conducted a study on the application of the SWAT model to assess the water balance of the Quaternary watershed located in the province of Northern Cape in South Africa. The semi-arid watershed's hydrological processes were not understood properly and differed a lot from humid to sub humid areas. The utilization of the SWAT model played a major role in understanding the intricate hydrological processes in the watershed. However, inadequate data for uncertainty analysis, model calibration and validation limited the model's application. The study, thus assessed the model's application in simulating water balance components in the basin. The model performance evaluation also showed acceptable ranges of values, NSE was 0.76 and R^2 was 0.78. Furthermore, the catchment's spatial-temporal variabilities of the various water balance components and the water stress intensity were quantified and evaluated.

Twisa et al., (2020) utilized the SWAT model to assess and predict the effect of land use changes on the hydrology of Tanzania's Wami river basin. The study showed a severe impact on the land use changes in the basin which has a crucial role in provision of water and food in the nation. The study's main objective was the examination of the impact of land use change on the hydrological processes in the watershed. Hybrid classification was conducted that included both supervised and unsupervised classification methods to process the Landsat images from 2000 to 2016 while Markov analysis was utilized in the simulation and forecasting of the 2032 land use. The study used both the Partial Least Squares Regression (PLSR) and the SWAT model to examine the impact of various classes of land use on the fluctuation of hydrological components. It was evident from the research, that land use across the watershed had changed since the year 2000 and was expected to continue until 2032. The hydrological impact of the land use in the watershed was also observed. The findings of the study indicate that the land use changes that had the most impact on the hydrological components include expansion of the built up area, increased land under cultivation and grasslands, and the reduction in the area covered by woodlands and forests during the period of the study. The findings of the study provide information that can assist the relevant stakeholders and key decision makers in land and water resources to make better decisions in management and planning of the catchment's use of resources.

Kimaru et al., (2019) evaluated the temporal variability of rainfall and stream flow into Lake Nakuru, Kenya using the SWAT model. The analysis of temporal variability of rainfall and discharge is essential in the determination of the likelihood of extreme events occurring such as flooding or drought and enables policy makers to mitigate their impact. Temporal variability of rainfall and stream flow into Lake

Nakuru were investigated in the study using hydrological and meteorological drought indicators from 1981 to the year 2018. The standardized evaporation index (SPEI) and the standardized precipitation index (SPI) characterized the meteorological drought while the stream flow drought index (SDI) characterized the hydrological drought. The study used the SWAT model to predict the stream flow of the five (5) tributaries of Lake Nakuru which include Nderit, Njoro, Makalia, Larmudiac and Ngosur rivers. The model was calibrated using 1984 to 1996 stream flow data from the Njoro river gauging station 2FCO5. The model's parameters were then validated using 1997 to 2007 stream flow data. The SUFI-2 algorithm was used in SWAT CUP for the model calibration. The performance of the model was good as the NSE and R^2 were both equal to 0.58 for the calibration period and 0.52 and 0.68 respectively for the validation period. The annual average water balance indicated that out of 823 mm annual rainfall received, 178 mm was the average annual water yield while 154 mm was surface runoff. The annual average evapotranspiration (ET) was 607 mm, The temporal variation results of the SDI and SPI for the five (5) sub basins showed that drought events identified by the 12 month SDI were almost all identified by the annual SPEI/SPI. At the watershed level, SPI showed an equal distribution of dry and wet periods with 50% negative and positive anomalies observed from 1981 to 2018. SDI observed wet periods on lower frequency (47.37%) and dry periods on high frequency (52.63%). The results of the variability in stream flow and rainfall indices show that the years between 2009 and 2018 were wetter than 1981 to 2008.

Chebet et al., (2017) carried out a study on the effect of land use change on river flows in Arror basin in Elgeyo Marakwet County, Kenya using the SWAT model. The primary data sources of the study were socioeconomic and remote sensing data. Landsat 5 data of 30 m resolution of 1986, 2000 and 2012 were used in the study. A

Digital Elevation Model of 90m was used in the catchment delineation of Arror basin. Secondary data was river discharge, soil and climate data. Questionnaires and field surveys were utilized in the collection of the socioeconomic data used for the study. The SWAT model was integrated with GIS to ascertain the effect of land use change on the quantity of water in the catchment. The calibration of the SWAT model indicated a NashSutcliffe Efficiency of 0.9 and R^2 value of 0.8. The results indicated a reduction of grassland by 11.8% and a reduction of deciduous forest by 3.5%. On the other hand, there was an increase in agricultural land by 14.3% from the year 1986 to 2012. The land uses of 1986, 2000 and 2012 yielded an average annual flow of 2.0, 2.5 and 1.9 m3/s respectively. The land use change contributed to the flow variation observed. The study recommended afforestation and agroforestry for the sustainable management of the basin.

Kibii, et al., (2021) utilized the SWAT model to evaluate the impact of land use and climate variability on the Kaptagat catchment river discharge. Climate variability, land cover, and land use changes have altered the hydrologic response of the Kaptagat catchment, one of the major sources of water for Eldoret. The study used the SWAT model to evaluate the impact of land use change and climate variability on the catchment yield, resulting in high variations in river flows and storage reservoir levels, and suggests possible mitigation measures to improve the yield. The model was customized for the study area, calibrated, and validated, and simulations were done to establish the changes in yield and river flow over time. The study observed that with time, land use changed due to increased settlement in the catchment, resulting in a decrease in forest cover (natural and planted) from approximately 37% in 1989 to 26% in 2019. Rainfall events also decreased but became more intense. The results of the changing land use and climate variability were changes in the catchment hydrologic response, occasioned by increased surface runoff and decreased baseflow and groundwater recharge, hence the high variations in water levels at the Ellegirini and Two Rivers dams in the catchment during the dry and wet seasons, as modeled.

2.9 Description of the WEAP Model

WEAP is a software tool that is user friendly and utilizes an integrated approach to planning and management of water resources. Challenges in management of freshwater have increased over the years. The allocation of finite water resources between, environmental, municipal and agricultural uses require, complete integration of water demand, water quality, water supply and ecological considerations. WEAP incorporates all these issues into a robust and practical manner to enable integrated water resource management and planning. The WEAP model was developed by the Stockholm Environmental Institute's Boston Center at the Tellus Institute (Loucks, 2005).

WEAP was developed in the year 1998 and is progressively updated by the Stockholm Environmental Institute (SEI) to further firmly enhance its ability to be a transparent, flexible and integrated tool for the assessment of the sustainability of current water supply and demand patterns by exploring long term scenarios (Yates et al., 2005). WEAP provides a user friendly, comprehensive and flexible framework for analysis of water policies put in place and a system that maintains information regarding water demand and supply.

WEAP is also a forecasting and prediction tool, that simulates water storage, flows, demand and supply. The model operates on the basic water balance principle and can be applied to agricultural and municipal systems, a single catchment or intricate trans boundary watershed systems (Amin et al., 2018). Furthermore, WEAP is able to simulate a broad range of both engineered and natural components of these systems which include; groundwater recharge, from rainfall, baseflow, rainfall runoff, water demand analyses, reservoir operations, water allocation priorities and rights, water quality and water pollution tracking (Agarwal et al., 2018)..

WEAP is a robust tool for evaluating alternative water management and development options. WEAP scenarios are used to explore the program with various “what if” questions including; what if the rules of reservoir operation altered? What if patterns in economic development and population growth change?

A reservoir is a body that is usually created by damming a river. Water is stored in reservoirs for use in irrigation, as a water supply, for Hydro-Electric Power (HEP) generation, recreation, or for flood control. Reservoirs in Kenya are mostly used for irrigation, flood control, water supply and HEP. Major cities in Kenya such as Eldoret and Nairobi rely on their water supply from reservoirs. Numerous dams have also been constructed in the Tana catchment for generation of hydroelectric power. Therefore, dams in Kenya are crucial in provision of a reliable and sustainable water source and are thus crucial components in hydroelectric schemes and public water supply (Masakha, 2017).

Storage in reservoirs is divided into four pools or zones which include, the inactive zone, buffer zone, conservation zone and flood control zone in an ascending order as indicated in Figure 2.3. The zones of buffer and conservation constitute the active storage of the reservoir. The WEAP model ensures that the flood control zone is always empty thereby ensuring that the volume of water in the reservoir cannot surpass the conservation zone as indicated in Figure 2.3.

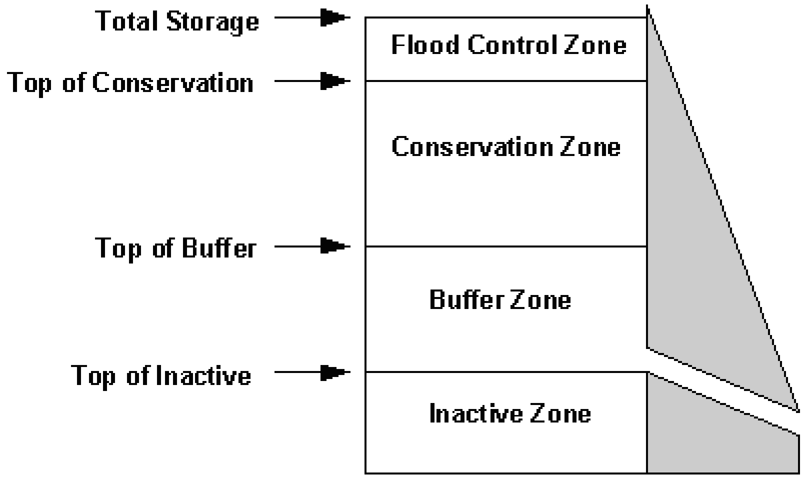


Figure 2.3 WEAP Reservoir Storage Zones Source: Yates et al., (2005).

The flood control zone storage (Sf) temporarily holds water that has to be released prior to the end of the time step and therefore spills storages above it. The zone of conservation storage (Sc) at its full capacity, is available for demands downstream. The buffer storage (Sb) is controlled to meet water demands during periods of water shortage. When the storage of the reservoir is within the buffer storage, the withdrawal of water is conserved through the buffer coefficient, bc, that ascertains the storage quantity available for release; the inactive storage (Si) is considered as dead storage since it cannot be utilized (Yates et al., 2005).

WEAP enables the reservoir to release water freely from the conservation zone to meet the downstream and withdrawal demands. Once the reservoir storage falls into the buffer zone, WEAP restricts the release of water via the buffer coefficient in order to preserve the dwindling supplies of the reservoir (Sieber, 2006). Water in the inactive zone is not available for allocation unless under really extreme conditions. Evaporation can be one of the causes that drops the water levels in the reservoir into the inactive zone.

The available amount of water to be released from the reservoir (Sr), (Eqn 2.1) is the total amount in the flood and conservation control zones a buffer coefficient fraction of the amount in the buffer pool (Yates et al., 2005).

Sr = Sc + Sf + (bc * Sb) ………………………………………………………. (Eqn. 2.1.)

Where Sr is total amount available to be released from the storage of the reservoir, conservation storage Sc, flood control storage is Sf, buffer coefficient is bc and buffer storage is represented by Sb.

2.10 WEAP Applications

Mounir, et al. (2011) carried out research on the Niger River in Niger Republic where the authors utilized WEAP to evaluate the future water demands on the river. In the study, the impact of future variation of climatic data i.e., stream flow, rainfall etc. was analyzed using WEAP's Water Year Method. The method entailed the definition of how various climatical regimes (e.g., very wet, wet, dry and very dry) compare to a normal year which is usually given a value of 3, and very wet areas assigned a value above 3. The authors then created the sequence of climatic changes of the scenarios. Every year of the scenario period was assigned a certain climate category e.g., dry for the Reference scenario. The model inflows i.e., head flows varied in time. The WEAP model offered two approaches where the detailed forecasts were available, they were read using the ReadFromFile function or the Water Year Method where the duration of the model are only defined as wet, dry, very wet or very dry. Various scenarios can change from very dry to very wet to enable the user evaluate the natural variation impact on the water resources management. The results indicated that infrastructural development on water resources is essential since future water demand outstrips water supply.

Mehta, Aslam, Dale, Miller, & Purkey (2013) conducted a scenario-based study on water resources planning for the water utilities in the Lake Victoria region. At the time, the cities in the region were experiencing among the highest population growth rates in Africa and there was a rapid increase in water demand which was threatened by industrial pollution. Urban centers use Lake Victoria and local springs as their major water source. IWRM tools enable stakeholders and water utilities develop a comprehensive enough planning framework that incorporates short term scenarios such as land use change and long-term scenarios such as climate change. The study showed IWRM Models developed using the WEAP model as a decision support system for three (3) towns in the Lake Victoria region including, Kisii in Kenya, Bukoba in Tanzania and Masaka in Uganda. The populations of the three towns at the time of the study were estimated as, 200,000, 100,000 and 70,000 respectively. The demand coverage was 50% in Kisii town and 70% in Bukoba and 80% in Masaka. The models for each town were calibrated via performance of the system based on interviews, utility reporting and site visits. Projected water demand, supply, costs and revenues were then assessed against infrastructure, demographic and climate scenarios up to 2050 which was very essential in assisting the water utilities in water resource planning for the three towns.

Akivaga (2010) conducted a research on WEAP simulation and scenario analysis of water resources in the Perkerra watershed. The study evaluated the current management scenario of water resources and its impact on the proposed infrastructural developments in the basin. The main objective of the study was the application of the WEAP model in the basin, evaluation of the effects of proposed development projects, regulation and policies under numerous scenarios in accordance with the 2002 Water Act. Water use and hydrometeorological data was sourced from Kenya Meteorological Department (KMD), the Ministry of Water and Irrigation, the Perkerra Irrigation Scheme and the Water Resources Management Authority (WRMA). The data collected was geo-referenced in the Arc View GIS software and a spatial database was created. The FAO Rainfall-runoff method was utilized in the simulation of the runoff. The watershed was divided into three major sub basins where the demand nodes and basin runoff were located spatially. Two major scenarios were developed from the reference scenario; Water development scenario and Chemsusu Dam. Further, three sub scenarios were developed to assess the enhanced irrigation efficiency in the Perkerra irrigation scheme, current levels of water abstraction and the increased water demands. The observed flows at the Marigat station were used to validate the reference scenario results. The results showed sharp peaks in the downstream flow and increased susceptibility of the demand nodes with a varying demand coverage between ten and a hundred percent.

Sum (2014) conducted a study on modeling Chebara Dam's water supply and demand using the WEAP model. The main objective of the research was to model the reservoir's water demand and supply so as to examine the effect of the different water demand options on the dam. Water use and hydrometeorological data was sourced from the Eldoret Water and Sanitation Company (ELDOWAS), the Kenya Meteorological Department (KMD) and the Water Resources Authority. The data collected was geo-referenced using the Arc View GIS software to create a spatial database. The simulation of the runoff was done using FAO's Rainfall-runoff method. The WEAP model lumped the catchment into one where the demand nodes and basin runoff were spatially located. Three major scenarios were built from the reference scenario including; climate variability scenario, Chebara dam's infrastructural development and the population growth scenario. The major water demand point which is Eldoret town and the observed reservoir levels of the Chebara reservoir were then used to validate the results of the reference scenario. The results showed sharp peaks in the downstream flow and increased susceptibility of the demand nodes with a varying demand coverage between ten and a hundred percent.

The SWAT and WEAP models were selected for this study because of their robustness and ease of use depending on data availability. The models are reviewed briefly in the following sections i.e. sections 2.7 and 2.9 describing the SWAT and WEAP models respectively. They are among the few decision support systems that have been applied on numerous studies on river basis and watershed management.

Water resource management models such as the Soil & Water Assessment Tool (SWAT) model are essential tools that are used to generate continuous estimates of streamflow and other hydrological variables. In this study for instance, the SWAT model was used to generate simulated river flows draining to the Two Rivers and Ellegerini Reservoirs as an input to the WEAP model. Furthermore, in order to analyze the spatial effect of water allocation and water demand in a catchment, it is essential to use distributed models. WEAP takes into consideration supply preferences and demand priorities in a linear programming heuristic to provide solutions to water allocation problems as an alternative to logic approaches based on rules or multi criteria weighting. The model entails a transparent set of model procedures and objects and utilizes them in a scenario-based approach to evaluate various issues facing water planners. WEAP was therefore selected for this study as the appropriate water resource management model for water allocation due to its robustness, versatility and its ease of use depending on data availability. Additionally, the WEAP model can also handle aggregated to disaggregated water management demands of various sectors and is thus essential in the study of catchments with moderate to minimum data availability.

2.11 The WEAP Model Selection Criterion for this Study

The WEAP model was selected for this study. The WEAP model was preferred to other hydrological models such as MIKE Basin, MODSIM, MULti-sectoral, INtegrated and Operational Decision Support System (MULINO – DSS), Water Balance Model (WBalMo) and River Basin Simulation Model (RIBASIM) due to its robustness and because it is easy to use depending on data availability. Additionally, the WEAP model can also perform both distributed and lumped hydrological simulation of a river basin. Furthermore, the software tool can also handle both disaggregated and aggregated demands of water management of different sectors. The model was therefore crucial for examining watersheds with moderate or minimal data availability such as the Two Rivers Dam catchment. The model was therefore selected for this study with consideration of cost implications and data availability in the watershed.

The WEAP model is an effective IWRM model because it takes an integrated approach to water resources planning and also because it is user-friendly, easy to-use, affordable, and readily available to the wider water resource community (Yates et al., 2005).

2.12 Gap in Knowledge

WEAP uses three methods to simulate watershed processes which include the soil moisture method, the rainfall runoff method and FAO’s crop requirement approach of irrigation demands only. The above-mentioned researches by (Sum, 2014) and (Akivaga, 2010) on the WEAP Model applications used the rainfall-runoff method for the simulation of their catchment processes. Additionally, Akivaga (2010) and Sum (2014) did not determine the impact of land use and land cover changes on their respective catchments. The gap in knowledge that was contributed by this research, is that it did not only use the Soil Moisture Method for the simulation of the Two Rivers Dam catchment processes but also determined the effect of land use and land cover changes in the basin. Moreover, because there was inadequate stream flow data in the catchment, the SWAT model was utilized in the generation of the simulated flows in the basin as an input to the WEAP model. The most complex of the three WEAP simulation methods is the Soil Moisture Method which represents the basin with two soil layers. In the upper soil layer, WEAP simulates evapotranspiration in consideration of irrigation and rainfall on non-agricultural and agricultural land, shallow interflow and runoff, and soil moisture changes. The routing of baseflow to the river and changes in soil moisture are simulated in the lower soil layer. This technique requires substantially more climate and soil parametrization to simulate the catchment processes. The method was chosen for this research because it is the most effective method that enables the user to comprehensively assess soil type and land use impacts on the catchment processes (Yates et al., 2005).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

This chapter presents the methods and procedures that were applied in the achievement of the objectives of this study. It gives details of the types of data that were used, data collection methods, the sourcing of input data and the techniques that were used to analyze and process the data. The overall methodology involved the model set up and the calibration and validation of the SWAT and WEAP models. Finally, the statistical methods which were used for analysis of model performance were presented.

3.2 Study Area Details

The Kaptagat Forest catchment is part of the larger Cherangany Forest Ecosystem, one of the Kenya's five (5) water towers. It is located in Elgeyo Marawket county (Kenya Forest Service, 2014). The Kaptagat forest is the source of the Ellegerini river which flows to the Ellergini and Two Rivers Dams as indicated in Figure 3.1. Additionally, the construction of a new dam has been proposed in the catchment which will be called the New Two Rivers Dam and is also shown in Figure 3.1. Moreover, the catchment has two river gauging stations, the Ellegerini and Endoroto river gauging stations shown in Figure 3.1. Furthermore, the catchment has five rainfall stations which include; the Eldoret Meteorological Station, the Kaptagat Station, the Eldoret Institute of Agriculture Station, the Kipkabus station and the Kaptagat Sabor stations as indicated in Figure 3.1.

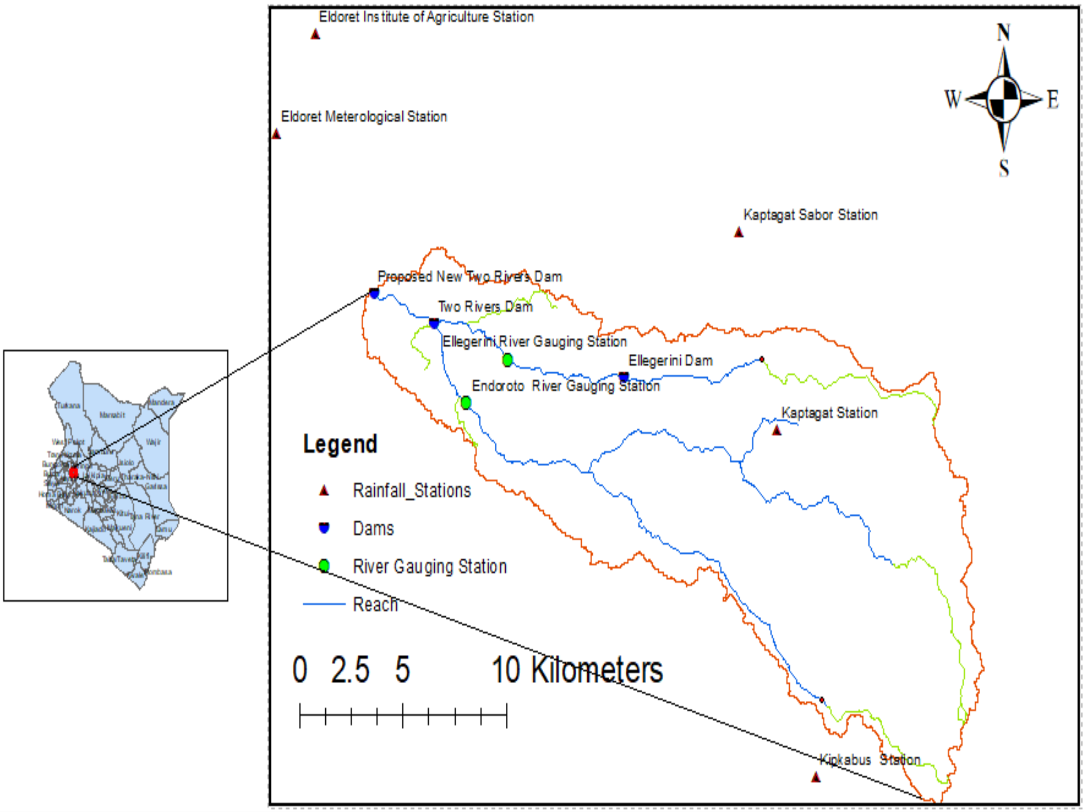


Figure 3.1 Map of the Two Rivers Dam catchment

The proposed infrastructural development in Eldoret is the Proposed New Two Rivers Dam (Figure 3.1) with a capacity of 57,500 m^3/d which is set to be completed by 2025. The New Two Rivers Dam will be located 700 meters downstream of the existing Two Rivers Dam. Initially treatment works capacity for The New Two Rivers Dam by 2025 will be 28,750 m3/d. However, it will be extended to full capacity of the Dam in 2035 (MIBP, 2018). The Lake Victoria North Water Works Development Agency (LVNWWDA) has procured a consultant for the final design, tendering and supervision. This will also see the construction of a new treatment plant at Sosiani, with a capacity of 28,750 m^3/d. A further 28,750 m^3/d capacity treatment plant will be constructed in 2035. The reservoir expected under the Eldoret Water Master plan is expected to cost Kshs 4.87 Billion and to come online in 2025. The maximum water capacities of the reservoirs in the catchment are indicated in Table 3.1.

Table 3.1: Maximum Capacities of Two Rivers and Ellegerini Reservoirs

No.	Water Sources	River	Treatment Plant	Maximum Capacity (m^3/day)	Current Production (m^3/day)
1	Two Rivers Dam	Sosiani	Sosiani	14,950	14,200
2	Ellegerini Dam	Ellegerini	Kapsoya	7,000	6,700
			Naiberi	2,000	1,800
	Total			23, 950	22,700

Ellegirini and Two Rivers Dams are the major reservoirs in the catchment. Ellegirini also doubles up as a reserve reservoir for recharging the downstream Two Rivers dam during low flows, and helps manage silt loading in to the latter dam. The Two Rivers Dam is a mass concrete dam with a height of 27.8m and a maximum storage of 12.7 Million Cubic Meters (MCM) that was constructed in 1960, along with a 6,100 m^3/d capacity gravity pipeline. The Ellegirini dam was constructed upstream of the Two Rivers Dam, and was completed in 1995 with an outlet pipeline capacity of 9,000 m^3/d. The Ellegirini dam is a 24.1 m high earth fill embankment dam with a maximum storage capacity of 2.3 MCM (MIBP, 2018). The Ellegerini river gauging station is located downstream of the Ellegerini Dam as indicated in Figure 3.1. This was a limitation of the study since there is no river gauging station upstream of the Ellegerini Dam. Therefore, the limitation was brought about by the lack of data collection of streamflow data upstream of the Ellegerini Dam. However, ELDOWAS, the water utility in the study area, provided water abstraction data for the Ellegerini Dam that was factored in the streamflow draining to the Two Rivers Dam.

There also exists the old Elllegerini (Pombo) intake on the Ellegerini river at the edge of the Kaptagat forest. It was developed in 1928 and had an initial installed capacity of 2,300 m^3/d. The intake has since been decommissioned and is no longer used by ELDOWAS. It has been handed over to the local community for their water supply.

Three treatment works exist within the ELDOWAS water supply system. The Kapsoya Treatment works, constructed in 1928, treated the water from the Ellegerini intake prior to distribution. The treatment plant was upgraded in 1981 and treats water from the Ellegerini dam. It has a design capacity of 7,000 m^3/d. The Kapsoya site also handles 16,000 m^3/d of storage from the Chebara treatment plant on transit to Eldoret town. In addition, the Naiberi/Cherunya Treatment Works has a design capacity of 2,000 m^3/d and also treats water from the Ellegerini dam. The Two Rivers Dam supplies the Sosiani Treatment Plant with a 14,950 m^3/d design capacity.

ELDOWAS is the registered water service provider for Eldoret. Existing infrastructure has the capacity to deliver 54,000 m^3/day although the current supply is closer to 48, 000 m^3/day which is 80% of demand (Uasin Gishu CIPD, 2018-2022). The main water source is the Moiben/Chebara Dam on the Moiben river which is located in Elgeyo/Marakwet County.

The current surface water supply to Eldoret is sourced primarily from the Moiben Dam (53%), Two Rivers Dam (29%), and Ellegirini Dam (18%). This implies that the main catchments of interest are associated with the Moiben and Sosiani river systems.

3.3 Development of a SWAT Model to Generate Flows as an Input to the WEAP Model

3.3.1 SWAT Model Inputs

The SWAT model was used to generate simulated river flows draining to the Two Rivers and Ellegerini Reservoirs as an input to the WEAP model. In numerous developing nations, there is a challenge in hydrological data availability and therefore the WEAP model cannot be directly applied and mostly requires input from different models like SWAT scarcity (Maliehe & Mulungu, 2017). This is the case particularly with the Two Rivers Dam catchment, where there is insufficient stream flow data. Therefore, the strategy of the study was first to quantify the stream flow using the SWAT hydrological model and then allocate water resources using the WEAP model to different water demands.

The basic SWAT model inputs required to achieve this objective include rainfall (mm), maximum and minimum temperature, solar radiation, wind speed, soil, land cover, relative humidity and elevation (DEM) (Cao et al., 2006). The basin is subdivided into sub basins that are related spatially thereby preserving the natural configuration of flow paths and natural channels.

SWAT model outputs include; sediment yield, flow generation and non-point-source loadings from each HRU in a sub basin which are then added up or combined. The summed-up loadings are then routed to the watershed outlet, through channels, ponds, and reservoirs that may be defined within the watershed. The key component of SWAT that is of interest to this study is hydrology.

The SCS CN method was used in the SWAT model to estimate precipitation losses and direct runoff. The runoff was then used to compute the quantity of rainfall that turns into stream flow and eventually flows into the Two Rivers and Ellegerini reservoirs which was then used as an input into the WEAP model.

3.3.2 SWAT Model Structure

Hydrological simulation of a catchment in SWAT is subdivided into two main divisions. The land phase of the hydrological cycle constitutes the first division while the second division entails the hydrological cycle’s routing phase. The hydrological cycle’s land phase controls the amount of nutrients, sediment, pesticide and water on the main channel in each sub basin whereas the routing phase defines the movement of nutrients, sediment, pesticide and water through the network of the channel of the basin to the catchment outlet (Nietsch S.L., 2005).

The water balance equation denoted by Equation 3.1 describes the basis of hydrology in the model:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{deep} + Q_{gw}\right) \qquad \textbf{Equation 3.1}$$

Where; SW_t denotes the final water content in the soil in mm H_2O, SW_0 is the soil's initial water content on day t= 0 and, i = 1, ***i*** in mm H_2O and t, the time in days, R_{day} represents the amount of rainfall in mm H_2O on day ***i***, ***Qsurf*** is day ***i's*** surface runoff in mm H_2O, E_a is the evapotranspiration amount in mm H_2O on day ***i***, W_{deep} is the amount of groundwater percolating on day ***i***, into the deep aquifer in mm H_2O and Q_{gw} is the amount of return flow on day ***i*** (mm H_2O). Runoff is then predicted for each HRU squarely and routed to get the total runoff in the river basin (Pai & Saraswat, 2011).

SWAT is a semi distributed model in that, sub basins are spatially related and will contain at least one HRU, a main channel and a tributary channel. The next subdivisions are the HRU's. These are portions of a sub basin that have unique land use/ land cover, slope and soil characteristics (Krysanova & Srinivasan, 2014).

Additionally, although individual HRUs may be scattered throughout a sub basin, their areas will be lumped together to form one HRU. These units are the ones that account for the spatial diversity in the basin characteristics. The assumption made is that the HRUs in one sub basin do not interact with each other (Ahn et al., 2016). The contributions from each HRU are calculated discretely and then summed up together to ascertain the total loadings from each sub basin. Inputs used to model processes within the catchment in the SWAT model are defined at three levels. These are the watershed level, the sub basin level and the HRU level.

The method used to model each process is uniform for all HRUs in the catchment, while inputs like rainfall and temperature are set at the same value for all HRUs in the particular sub basin. At the HRU level, land use and soil inputs are set to unique values for each HRU in the basin.

The amount of surface runoff in SWAT is estimated by either using the Green & Ampt infiltration or the SCS curve number method. The SCS curve number technique is an empirical method that estimates the runoff amount among varying soil and land use types. The SCS curve number (CN) is a function of the permeability of the soil, antecedent water conditions of the soil and the land use.

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$$ **Equation 3.2**

Ia is approximated as ***0.2S*** therefore the accumulated excess runoff becomes

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)}$$ **Equation 3. 3**

Where;

- Q_{surf}- is the excess rainfall or accumulated runoff (mm H_2O),
- R_{day}- is the day’s rainfall depth (mm H_2O),
- I_a -is the initial abstraction including infiltration, interception and surface storage, prior to runoff (mm H_2O), and
- S is the retention parameter (mm H_2O).

The retention parameter spatially varies because of changes in land use, slope and soils. Temporally variations to this parameter also occur due to changes in the water content in the soil. The retention parameter is represented by;

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$ **Equation 3.4**

Calculation for the rates of peak flow is done using the rational formula;

$$q_{peak} = \frac{\alpha_{tc} \times Q_{surf} \times Area}{3.6 \times t_{conc}}$$ **Equation 3.5**

Where;

- q_{peak} -is the peak runoff rate (m3/s),
- α_{tc} -is the fraction of daily rainfall that occurs during the time of concentration,
- Q_{surf} -is the surface runoff (mm H_2O),
- Area is the subbasin area (km^2),
- t_{conc} -is the time of concentration for the subbasin (hr) and
- 3.6 is a unit conversion factor.

In this study SWAT was implemented through the ArcSWAT graphical user interface. This program provides an interface within the ArcGIS geographic information systems (GIS) software to facilitate data input and SWAT input file preparation. ArcSWAT uses the topographic data (DEM's) to delineate the basin into sub basins and extract other inputs like slope classes, stream geometry and elevations. More details can be found in the SWAT Theoretical Documentation by (Neistch S.L., 2011) and (Arnold, 1998).

3.3.3 Goodness of Fit Statistics

There are numerous indices of statistical errors that are commonly used in evaluating a model which majorly include Root Mean Square Error (RMSE), Mean Square Error (MSE) and Mean Absolute Error (MAE). The indices are essential as they show the unit errors or square unit errors of the constituents of interest which enhances result analysis. Zero values of RMSE, MSE and MAE show a perfect fit and MAE and RMSE values of less than half of the standard deviation of the data measured is considered as low.

1. **BIAS**

Bias is a measure of the mean tendency of the data simulated to be smaller or larger than their observed values. The Bias optimum value is 0.0, with values of low magnitude indicating accuracy in simulation of the model. Model underestimation is shown by positive values while model overestimation is denoted by negative values. Bias calculation is denoted by Equation 3.10;

$$\boldsymbol{BIAS} = \left[\frac{\sum_{i=1}^{n} Y_i^{obs} - Y_i^{sim}}{\sum_{i=1}^{n} Y_i^{obs}}\right] \qquad \textbf{Equation 3.10}$$

Where; $\boldsymbol{Y_i^{obs}}$ are the observed values and $\boldsymbol{Y_i^{sim}}$ are the simulated values. Bias is the deviation of data being assessed.

Where; $\boldsymbol{Y_i^{obs}}$ are the observed values and $\boldsymbol{Y_i^{sim}}$ are the simulated values, and *n* is the total number of observations.

2. **Nash-Sutcliffe efficiency (NSE):**

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance in comparison to the measured data variance. NSE shows how good the plot of observed versus simulated data fits the 1:1 line. It is a measure of how well the observed and simulated values match NSE and is given by the equation 3.11;

$$\boldsymbol{NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{obs\,mean}\right)^2}\right]}$$ **Equation 3.11**

Where; $\boldsymbol{Y_i^{obs}}$ is the $\boldsymbol{i}$ th observation value, $\boldsymbol{Y_i^{sim}}$ is the $\boldsymbol{i}$ th simulated value $\boldsymbol{Y_i^{obs\,mean}}$ is the mean of observed data values, and $\boldsymbol{n}$ is the total number of observations.

NSE values range between −∞ and 1. Values between 0.0 and 1.0 are generally viewed as "acceptable" performance levels, and values less than 0 indicates that the mean observed value is a better predictor than the simulated value, which suggests a performance that is unacceptable. NSE values that are moving towards 1 indicate better model performances. (Anh, et al., 2008) (Moriasi, 2007), (Krause P., 2005) (Amir., 2013).

3. **Coefficient of determination R^2**

The coefficient of determination R^2 measures the variability proportion in the observed stream flows that is accounted for by the model. The R^2 value can range from 0 to 1, with higher values implying a better performance of the model (Wang *et al.*, 2010).

$$\boldsymbol{R^2 = \frac{\left(\left(Y_i^{obs} - \bar{Y}^{obs}\right) \times \left(Y_i^{sim} - \bar{Y}_i^{sim}\right)\right)^2}{\sum\left(Y_i^{obs} - \bar{Y}^{obs}\right)^2 \times \sum\left(Y_i^{sim} - \bar{Y}^{sim}\right)^2}}$$ **Equation 3.12**

Table 3.2: Threshold Values of Bias, NSE and R^2

Goodness of Fit Statistic	Range	Acceptable Performance Values
Bias	0 to 1	≤ 0.5
NSE	−∞ to 1	≥ 0.5
R^2	0 to 1	≥ 0.5

3.4 Determination of the Impact of Land Use and Land Cover Changes in the Two Rivers Dam catchment

3.4.1 Data Requirements

The data required to achieve this specific objective includes rainfall data, stream flow data, land use and land cover data, temperature data, soil data, satellite images (Landsat ETM +) and DEM data. In addition, the following software; the SWAT hydrological modeling program, ArcGIS and Microsoft Excel were used to achieve this specific objective.

3.4.2 Data Collection and Analysis

It is difficult to obtain extensive data sets on all hydrological process variables at the required time and at the spatial-scales needed to capture vital catchment wide hydrological processes. The engineering hydrologist, therefore as a modeler faces enormous challenges brought by limited availability of good data. In an effort to overcome this problem, this research used data that was collected from various institutions in addition to downloading some of the data from online databases. The daily rainfall data of the simulation period from 1989 to 2020 was obtained from both the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), the National Oceanic and Atmospheric Administration (NOAA) and the Kenya Meteorological Department (KMD). The rainfall data had gaps which were filled through interpolation in Microsoft Excel. The rainfall data was also checked for temporal consistency in comparison with also satellite rainfall data and the inconsistencies were corrected accordingly. The average rainfall of the catchment was 1247mm. Furthermore, the soil data was sourced from the Kenya Soil and Terrain (KENSOTER) database that was compiled by the Kenya Soil Survey (KSS) with support from the International Soil Resource and Information Center (ISRIC) at a scale of 1:1,000,000. Additionally, the digital elevation model (DEM) and GIS land cover datasets were downloaded from the United States Geological Survey (USGS) website. Moreover, the Landsat land cover land use satellite images at ten-year intervals for the past 31 years were downloaded from the USGS website and were chosen in the period December – February, which were the months that presented the least cloud cover thereby enhancing the quality of the satellite images. Additionally, observed daily discharge data for the simulation period from 1989 to 2020 and stream gauge heights for the Endoroto and Ellegerini River Gauging Stations (RGS) were obtained from the Water Resources Authority (WRA).

(i) Rainfall data

The available rainfall data was sourced from Kenya Meteorological Department (KMD) was analyzed for use based on the periods with high percentages of complete data. This was done for a number of stations (Table 3.3) that fell within and around the Two Rivers Dam catchment. Stations with little data were eliminated.

Table 3.3 Selected Rainfall stations (KMD)

STATION NAME	Station Number	Latitude	Longitude	Year Opened
Eldoret Meteorological Station	8935181	0° 32.67'N	35° 17.18'E	1972
Kaptagat Forest Station	8935010	0° 26.34'N	35° 30.61'E	1928
Kaptagat,Sabor Forest Station	8935164	0° 30.16'N	35° 29.18'E	1965
Kipkabus Forest Station	8935117	0° 19.73'N	35° 31.14'E	1951
Eldoret Institute of Agriculture Station	8935133	0° 34.96'N	35° 18.73'E	1954

(ii) Discharge data.

The discharge data from the Ellegerini (Station ID: 1CB09) and Endoroto (Station ID: 1CB08) River Gauging Stations were used in the calibration of the SWAT and WEAP models. The gauging stations are located on coordinates (0.456944^0 N, 35.383333^0 E) and (0.445833^0 N, 35.366667^0 E) respectively.

(iii) Baseflow Separation

Baseflow measurements were separated from daily streamflow data acquired from the river gauging stations using the automatic baseflow digital filter method (BFlow). (Aboelnour, Gitau, & Engel, 2020). The BFlow filter separates streamflow data into baseflow and surface runoff by passing the observed streamflow through the filtering equation three times

$$BF_t = \alpha \, x \, BF_{t-1} + \frac{1-\alpha}{2} \, x \, (Q_t + Q_{t-1}) \quad \text{[Eqn 3.13]}$$

where BF is the baseflow, α is the filter parameter (0.925), Q is the total streamflow, and t is the time step. Equation (3.13) is applied only when BF ≤ Qt. BFlow is a conservative filter that enables the user to filter streamflow data to calculate the baseflow, and also to generate a tabular dataset or graphical hydrograph interface from the river gauging stations. Herein, BFlow filtered streamflow data three times (Equation (3.13)), and it is commonly observed that the 1-pass baseflow is consistent with manually estimated baseflow and thus was subsequently used in this study (Aboelnour, Gitau, & Engel, 2020).

3.4.3 Satellite Image Analysis and Change Detection

Both temporal and spatial land cover changes were analyzed in the study. The satellite images were used to quantify land cover changes while the land and soil cover were used to determine the overland flow. The Curve Number (CN) is a function of the hydrologic soil group, land cover type and antecedent moisture conditions. To determine the curve number, the land cover and soil type coverage were combined through overlay analysis of GIS. The resulting coverage was then used to delineate the basin into sub areas that have the same land cover and soil type, known as Hydrologic Response Units (HRUs).

The satellite land cover change images were at ten-year intervals for the past 31 years (1989-2020) were chosen in the period December – February, which are the months that present the least cloud cover thereby enhancing the quality of the satellite images.

3.4.4 Digital Elevation Model Analysis and Processing

The Digital Elevation Model (DEM) was obtained from the United States Geological Survey (USGS) Website from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) sensor. The ASTER DEM images were then added into ArcGIS in order to be geo-referenced to the correct coordinate system and also for combination through mosaicking. The sinks and peaks were then removed through the fill command. The shape file was created using the raster to polygon conversion command which also showed the flow direction, flow accumulation and the stream networks. The slope was then determined using spatial referencing where the Universal Transverse Mercator (UTM) projection was used. The basin tool was then used to create a raster that located all sets of connected cells and pour points that drain to the same drainage basin and this was used to delineate the catchment.

3.4.5 Weather Data Definition

Before loading the climatic data the user weather generator station from the SWAT user weather generator database must be selected. Rainfall and temperature data were then loaded through the ArcSWAT interface. Here the various data sets from the weather stations were saved separately as text files with an accompanying batch file. These stations are assigned to the sub basins in the watershed based on how close a station is to the sub basin. The last stage in the model set up is the writing of all the SWAT input files and executing the model run.

3.4.6 SWAT Model Scenario Analysis

SWAT scenario analysis was conducted where the forest cover of the land use of the year 2020 which is the latest study year (thereby simulating current conditions as opposed to past conditions) by 5% progressively. The impact of the increased forest cover was then analyzed in relation to the runoff and the baseflow. The results of the impact of increased forest cover on the runoff and baseflow are summarized in Table 4.9.

3.5 The Development, Calibration and Validation of the WEAP Model

WEAP uses three techniques to simulate catchment processes including infiltration, runoff, irrigation demand and evapotranspiration. The methods include; the Soil moisture method, the irrigation demands only approach and the rainfall runoff method. The soil moisture method was selected for the study due to its comprehensive analysis that allows characterization of the effect of land use and soil types on catchment processes (Yates et al, 2005).

3.5.1 Setting up the WEAP Model for the Two Rivers Dam catchment

The setting up of the WEAP model for the Two Rivers Dam catchment entailed establishment of the spatial boundaries, time frame and system components of the simulation period. The available water supply, water resources and current accounts of the water demand of the watershed were then determined. Furthermore, the reservoirs in the catchment which include Ellegerini Dam and Two Rivers Dam were modelled in the study. The inputs of the model include; reservoir inflows such as direct rainfall, surface runoff and stream flow; reservoir outflows such as water withdrawals, environmental flows and reservoir evaporation; simulation parameters including spillway capacity, initial storage, minimum storage level, storage-surface area relation and start of rationing levels were used in the WEAP model to assess the water balance of the reservoirs. In this regard, the model was used to simulate both the natural (e.g. evapotranspirative demands, runoff, base flow) and engineered components (e.g. reservoirs, water transfers through transmission links) of water systems, in the catchment. Moreover, the Model was used to simulate the water demand, supply, flows and storage under different management options and corresponding scenarios in the study area.

3.5.2 The WEAP Modelling Process

WEAP divided the basin into various irregular sub basins based on land use classes, climatological regions, watershed boundaries or combinations thereof. The hydrological cycle's conceptual model yielding stream flow is determined for each sub basin using a semi-distributed approach on water balance (Yates et al., 2005). WEAP's linear programming heuristic was used to model supply preferences and demand priorities to alleviate the water allocation problems in the watershed. A transparent set of model procedures and model objects was used through an approach based on the scenarios to assess the catchment's water supply challenges. The software package's accounting principles regarding water balance enabled program testing of the alternative sets of demand and supply conditions.

3.5.3 WEAP Model Calibration and Validation

Water allocation models are complex and are required to simulate the behavior of human beings to reflect water demand changes in addition to other physical processes which therefore means that calibration and validation of the models is very difficult and has been neglected many times in the past (McCartney and Arranz, 2007).

The observed stream flow data at Endoroto and Ellegerini River Gauging Stations was used to calibrate and validate the WEAP model. The flows present changes in water demand, land use change and infrastructural development in the catchment.

Model calibration is performed to check model performance and entails altering the parameters in the model to ensure better simulation of the historical patterns. WEAP does not support automatic calibration and therefore, the manual calibration was done by comparing the observed and simulated time series.

3.5.4 WEAP Model Performance Evaluation

The WEAP Model performance was assessed using standard statistics; mean error (ME), mean square error (RMSE) and model goodness of fit as indicated by the following equations.

1) Mean Error, ME: $$E = \frac{\sum_{i=1}^{N}(s_i - o_i)}{N}$$ [Eqn 3.13]

Where, o_i, s_i and $\bar{o}$ represents observed values, simulated values and mean of the observed values respectively for $i = 1$ to N, where N is the number of values.

2) Mean Square Error, MSE: $MSE = \left(\frac{\sum_{i=1}^{N} (s_i - o_i)^2}{N} \right)$ [Eqn 3.14]

The MSE shows how much the model simulations over-estimate or under-estimate the measurements.

3) Modelling Efficiency (EF): $EF = 1 - \frac{\sum_{i=1}^{N} (s_i - o_i)^2}{\sum_{i=1}^{N} \left(o_i - \bar{o} \right)^2}$ [Eqn 3.15]

The EF value compares the predicted values to the average measured values. EF ranges from - ∞ to 1 with higher values depicting better agreement. If EF is less than 0, the model-predicted values are worse than simply using the observed mean. The characteristics of the different statistical parameters are given in Table 3.3.

4) Goodness of fit, R^2: $R^2 = \left[\frac{\sum_{i=1}^{N} \left(o_i - \bar{o} \right) \left(s_i - \bar{s} \right)}{\sqrt{\sum_{i=1}^{N} \left(o_i - \bar{o} \right)^2} \sqrt{\sum_{i=1}^{N} \left(s_i - \bar{s} \right)^2}} \right]^2$ [Eqn 3.16]

Where, $\bar{s}$ is the mean of predicted values.

Goodness of fit (R^2) expresses the linear dependency of two variables. R^2 ranges from 0 to 1. The dependency is high if the correlation equals 1 and the dependency is low (no correlation) if the correlation equals 0. Correlation value describes the similarity of the modeled values with the observed values. As an expected outcome the correlation should be close to 1. The higher the R^2 value the greater the model performance. The characteristics of the different statistical parameters are given in Table 3.4

Table 3.4: Characteristics of the different statistical parameters

Statistical Parameter	Range	Value	Indication
ME	≤ 0	ME=0	Model is perfect
		ME<0	Model is less perfect
MSE	≤ 0	MSE=0	Model is perfect
R^2	0 – 1	R^2=1	Perfect
		R^2=0	No prediction capability
EF	- ∞ to 1	EF=1	Model is perfect
		EF < 0	No prediction capability

3.5.5 Sensitivity Analysis of the WEAP Model

Sensitivity analysis of the WEAP model was done to check the model input parameters. The analysis was done to check the influence of potential calibration parameters on the model performance. Therefore, single input parameters such as effective precipitation were varied in plausible ranges and the response of the model was evaluated. In calibration, the effective precipitation was determined by trial and error until a value that is acceptable is selected. Further, land use factors such as the reference crop evapotranspiration, ETo were modified during the calibration of the model. Sensitivity analysis of the model was then determined for the two WEAP input parameters. The parameter that when changed resulted in more discharge when a small percentage was varied in the model indicated that it was more sensitive to the model and the parameter when varied gave less discharge was not a sensitive parameter. The two parameters were optimized during the modeling exercise.

3.6 Application of the WEAP Model in Analyses of Management and Infrastructural Development Scenarios

Most watershed management models do not have in built scenario analysis tools that enable better management and water allocation planning. Testing various scenarios enhances management and planning for competing uses and is enabled by planning models such as WEAP. Scenarios are story lines of how a system evolves over time in future under a certain socioeconomic setting in particular technological conditions and set of policies. Comparing the alternative scenarios provides proper guidance to policy makers for local and regional water systems (Vogel et al., 2007).

The business as usual scenario also known as the reference scenario is the base scenario which uses the actual data, to better understand ensure the most optimum estimates of the study period. The reference scenario was used to ascertain what would likely occur if the current trend continues and to better understand the present situation in the study area.

Different "what if" scenarios that address the "what if" questions were created. A variety of land use and land cover change scenarios were created to determine their resulting effects on river flows to the Two Rivers and Ellegerini Reservoirs. Further, various management and infrastructural development projects scenarios were created to enhance river flow and water storage in the two reservoirs in the catchment. Additionally, various scenarios, options and alternative assumptions about effect of land cover and land use changes on water demand and supply and hydrology were evaluated.

The analyses of the above-mentioned scenarios provided a more comprehensive view of the wide range of factors that must be considered in the management of water resources for the current and future use in the basin as this was used to examine alternative water development and management options in the Two Rivers Dam catchment. The scenarios that were analyzed in this study include, the reference scenario, the infrastructural development scenario and the population growth scenario.

3.7 The SWAT and WEAP Model Conceptualization

The SWAT Model uses the SCS CN method to estimate precipitation losses and direct runoff. The amount of runoff contributing to stream flow was then determined and the volume of flow generated by the SWAT Model was used as an input in the WEAP model (Figure 3.2). The SWAT model generated flows for the Two Rivers Dam catchment which was then converted into *csv* format and used in the WEAP model.

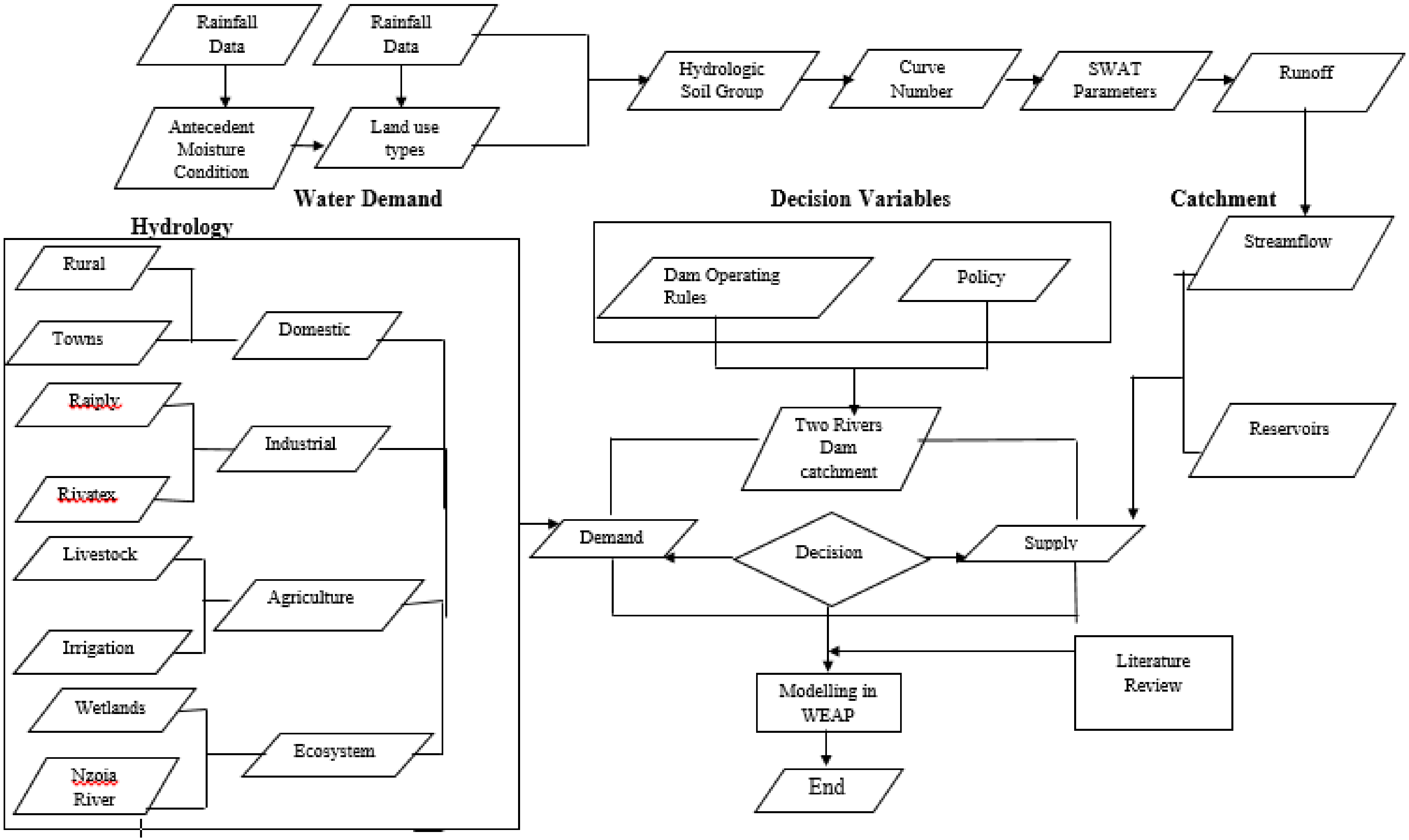


Figure 3.2 Conceptual Framework

3.8 The Specific Objectives and Variables Needed to Achieve the Objectives

The variables needs in achieving the specific objectives for the study are presented in Table 3.5.

Table 3.5: Variables needed to achieve the specific objectives of the study

Objectives	Variables needed to achieve Objectives
1. To set up and apply SWAT model to generate simulated river flows draining to the Two Rivers and Ellegerini Reservoirs as an input to the WEAP model.	Climatic data: rainfall, temperature and evapotranspiration Soil type Discharge Catchment yield
2. To determine the impact of land use and land cover changes in Two Rivers Dam catchment and the resulting effects on river flows to the Two Rivers and Ellegerini Reservoirs.	Land use change Land use map Initial reservoir storage volume Final reservoir storage volume Reservoir storage capacity
3. To set up, calibrate and validate a WEAP model for the Two Rivers Dam catchment.	Simulated river flows from the SWAT model Rainfall Time Series Discharge Reservoir Inflows (streamflow, surface runoff, direct rainfall) Reservoir Outflows (water withdrawals, environmental flows, reservoir evaporation)
4. To apply the WEAP model in analyses of various management and infrastructural development scenarios to enhance water storage in the Two Rivers and Ellegerini Reservoirs.	Proposed Reservoirs’ Storage Capacities Dam Operating Rules Water abstraction permits

3.8.1 The Independent, Intervening and Dependent Variables

The independent, intervening and dependent variables for the study are presented in Table 3.6.

Table 3.6: The independent, intervening and dependent variables for the study

Independent Variables	**Intervening/Decision Variables**	**Dependent Variables**
Precipitation	Dam Operating Rules	Reservoir Storage Levels
Temperature	Water Use Permits	Water Abstraction Quantities Evaporation
Reservoir Evaporation	Policies on regulation of water usage	Reservoir levels
Land Use Land Cover Change	Afforestation	Surface runoff
Initial Reservoir Storage Volume	Dam Operating Rules	Final Reservoir Storage Volume

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Development of a SWAT Model to Generate Simulated River Flows Draining to the Two Rivers and Ellegerini Reservoirs as an Input to the WEAP Model.

4.1.1 SWAT Model Setup

The SWAT model requires many input files. In order to generate these files, the ArcSWAT graphical user interface was used to extract information from geographically referenced maps in the ArcGIS environment. The process of setting up the SWAT model included defining a project folder, loading the DEM, rainfall, temperature, soil and land use data through the ArcSWAT interface (Kimani, 2014). The DEM for the Two Rivers Dam catchment is shown in Figure 4.1. The interface is used to generate the stream network and delineate the watershed boundary from the DEM and further subdivide the basin into sub basins. The land cover and soil layers were used to generate HRUs. The climatic data was also spatially integrated to allocate these data as the key model drivers to the numerous sub basins (Shi et al., 2013).

The first step was to load the digital elevation model (DEM) that was projected to the UTM zone 36N projection system. After this DEM processing which includes filling sinks, slope generation, flow direction and flow accumulation was done. The stream network was generated after assigning a threshold area that determined the number of cells required to initiate a stream. Lower threshold values lead to denser stream networks and vice versa. The Two Rivers Dam catchment was then delineated into its respective sub basins as indicated in Figure 4.2. Once the sub basins were delineated the sub basin parameters (longest flow path, basin centroid and slope) were calculated.

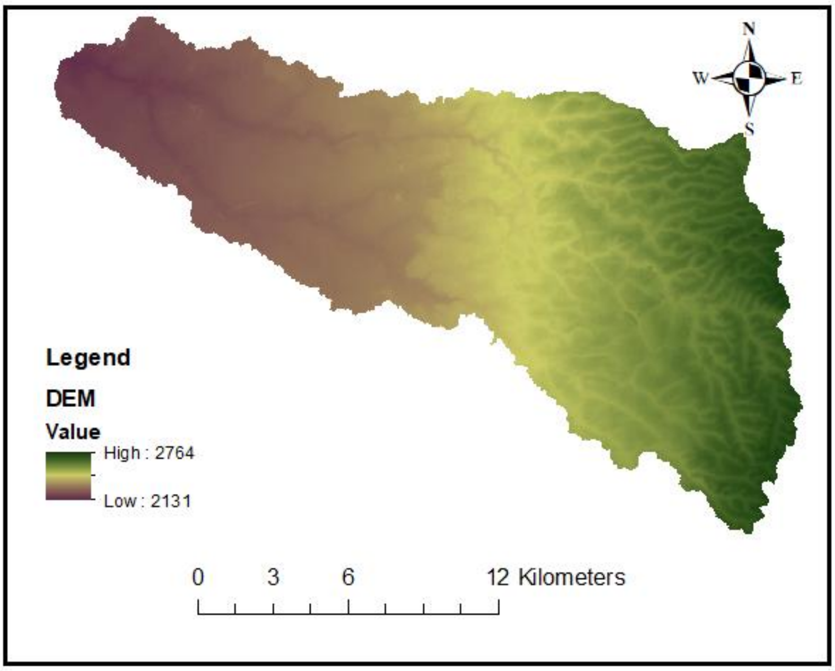


Figure 4.1 Two Rivers Dam catchment Digital Elevation Model

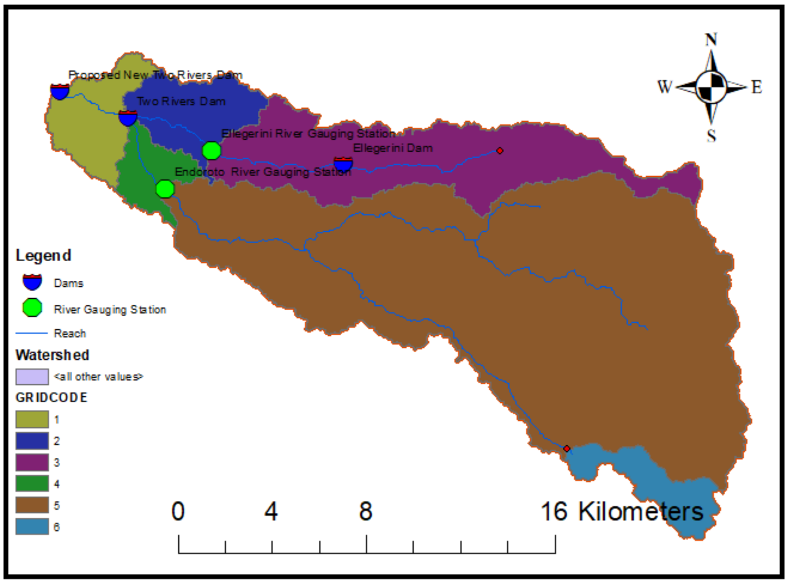


Figure 4.2 Two Rivers Dam catchment Sub Basins

4.1.2 SWAT Model Parameters

SWAT model parameters related to hydrology that were considered during and after the model setup that were considered for the generation of the river flows are summarized in the Table 4.1.

Table 4.1 SWAT parameters for simulation of flow

Flow related parameters

Parameter	Definition	Process	Level	Range
ALPHA_BF	Base flow recession factor (1/day)	Groundwater	HRU	0–1
BLAI	Maximum potential leaf area index for crops	Plant Growth	HRU	0–12
CANMX	Maximum canopy index (mm)	Evapotranspiration	HRU	0–10
CH_K2	Hydraulic conductivity in main channel (mm/h)	Routing	Subbasin	0–150
CH_N	Manning coefficient for channel	Routing	Subbasin	0.001–0.1
CN2	SCS runoff curve number for moisture condition II	Surface Runoff	HRU	35–98
EPCO	Plant uptake compensation factor	Evapotranspiration	HRU	0.01–1
ESCO	Soil evaporation compensation factor	Evapotranspiration	HRU	0–1
GW_DELAY	Groundwater delay (days)	Groundwater	HRU	0–100
GWQMN	Threshold storage in shallow aquifer for return flow (mm)	Groundwater	HRU	0–5000
GW_REVAP	Groundwater 'revap' coefficient	Groundwater	HRU	0.02–0.2
RCHRG_DP	Groundwater recharge to deep aquifer (fraction)	Groundwater	HRU	0–1
REVAPMN	Threshold storage in shallow aquifer for 'revap' (mm)	Groundwater	HRU	0–500
SLOPE	Average slope steepness (m/m)	Lateral Flow		
SLSUBBSN	Average slope length (m)	Concentration Time		
SOL_ALB	Soil albedo	Evapotranspiration	HRU	0–1
SOL_AWC	Available water capacity of the soil layer (mm)	Soil Water	HRU	0–0.3
SOL_K	Soil conductivity (mm/h)	Soil Water	HRU	0–15
SOL_Z	Depth from the soil surface to the bottom layer (mm)	Soil Water	HRU	0–12
SURLAG	Surface runoff lag coefficient	Surface Runoff	subbasin	0.01–24

4.1.3 Sensitivity Analysis

Sensitivity analysis was conducted on parameters of the model by using the SWAT model's one-factor-at-a-time (OAT) procedure for sensitivity analysis (Van Griensven et al., 2006). The list of sensitive parameters was then calibrated against the runoff data observed at the two river gauging stations in the catchment which include the Endoroto and Ellegerini RGS. Using more river gauging stations improves the efficacy of the calibration of the model thereby increasing the spatial variance representation of the model (Cao et al., 2006). Years 1978-1979, 1980–1984 and 1985–1989 were treated as the warm-up, calibration and validation periods, respectively. The 2016 land use map was used for model calibration and validation as it was the most accurate because it was already categorized beforehand. The daily, monthly and annual runoff was calculated and evaluated from observed data from Ellegerini and Endoroto gauging stations during model calibration and validation using three indices including namely, bias, coefficient of determination (R^2) and Nash-Sutcliffe coefficient of efficiency (NSE). When there is consistency in the three indices with the monthly time step criteria (NSE> 0.5, R^2 > 0.7, Bias <±0.25), the model was regarded as applicable to the watershed and to the effect of analyses (Moriasi et al., 2007).

The SWAT model was calibrated using 1980 to 1984 data because that is the period where there was more data rainfall data availability with less gaps in the data.. Before calibration of the model, sensitivity analysis using the 'One-factor-At-a Time' (OAT) design was conducted. The resulting sensitivity for the first round of calibration is represented and ranked in Table 4.2.

Table 4.2 Sensitivity Ranking of SWAT Model Parameters

Parameter	Rank	Description
Cn2	1	SCS runoff curve number
Sol_Awc	2	The soil layer's available water capacity.
Esco	3	Soil evaporation compensation factor.
Alpha_Bf	4	Base flow alpha factor (days).
Gwqmn	5	Threshold depth of water in the shallow aquifer required for return flow to occur.
Gw_Delay	6	Groundwater delay (days).
Gw_Revap	7	Groundwater revap coefficient.
Rchrg_Dp	8	Groundwater recharge to deep aquifer (fraction)
Surlag	9	Runoff lag time
Revapmn	10	Threshold storage in shallow aquifer for 'revap' (mm)

4.1.4 Model Calibration

The visual representation of the observed and simulated flow hydrographs for the calibration period is shown by Figure 4.3. The flow hydrograph for the period of calibration shows an underestimation of the simulated flow values. The line of best fit in the scatter plot for the simulated flows against the observed flows indicated in Figure 4.4 shows that the number of points above the line and below the line are almost equal. This indicates that the simulated values match well with the observed value as also attributed to by the high R-squared value of 0.854 in the monthly scatter plot indicating good model performance and that the model was effective in simulating the observed conditions.

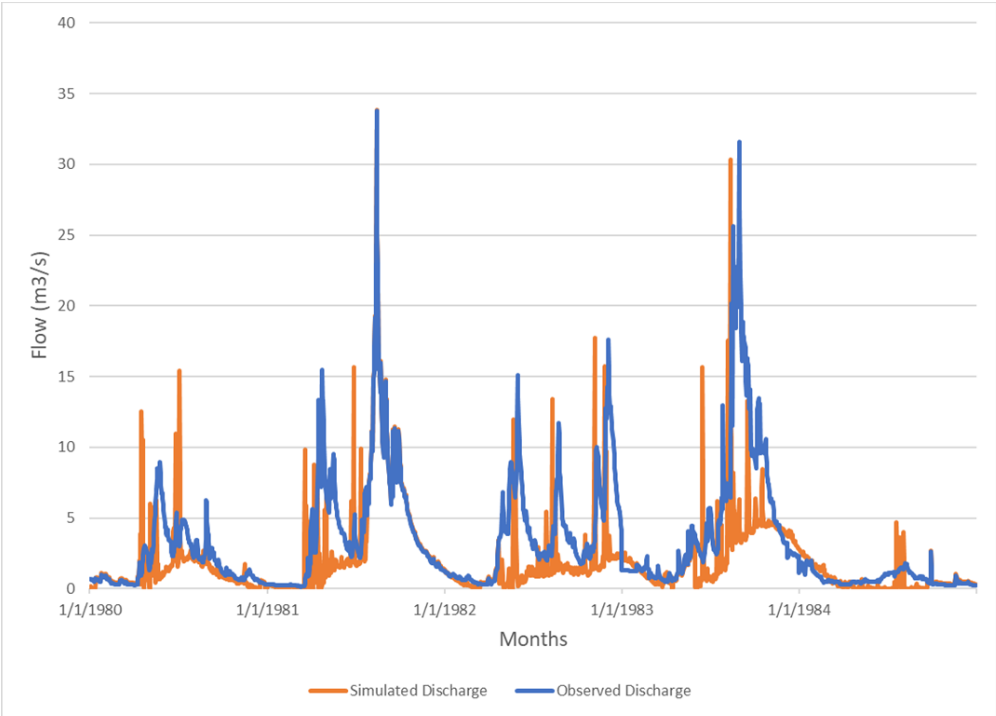


Figure 4.3 SWAT Model Calibration Graphical Results

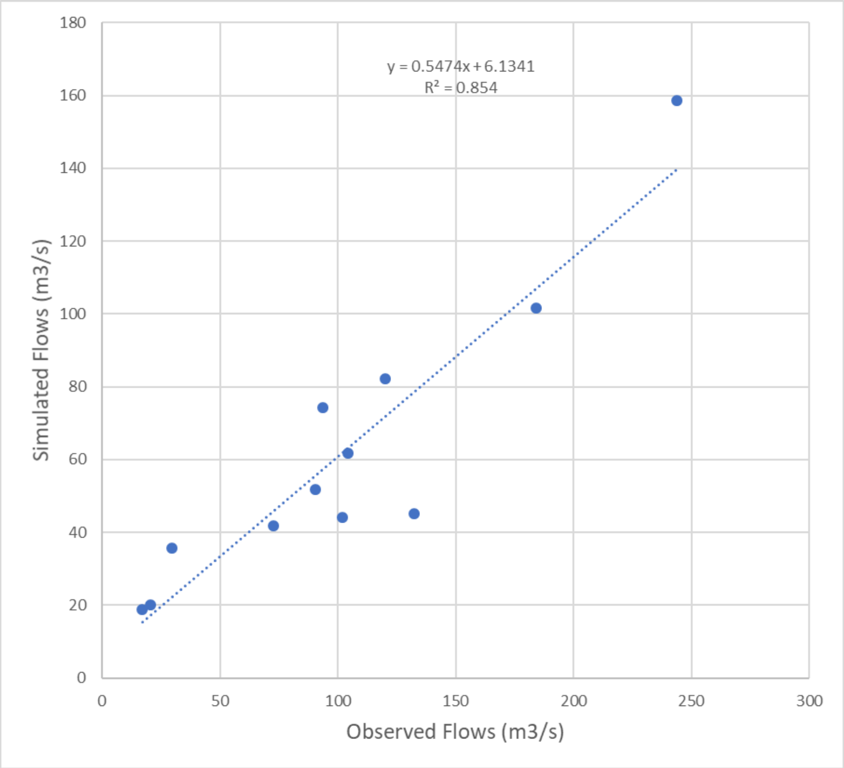


Figure 4.4 Scatter Plot for Calibrated SWAT Model Results

4.1.5 Model Validation

The visual representation of the observed and simulated flow hydrographs for the validation period is shown by Figure 4.5. The flow hydrograph for the period of validation shows an underestimation of the simulated flow values. The line of best fit in the scatter plot for the simulated flows against the observed flows indicated in Figure 4.6 indicates that the number of points above the line and below the line are almost equal. This indicates that the simulated values match well with the observed value as also attributed to by the high R-squared value of 0.786 in the monthly scatter plot indicating good model performance and that the model was effective in simulating the observed conditions.

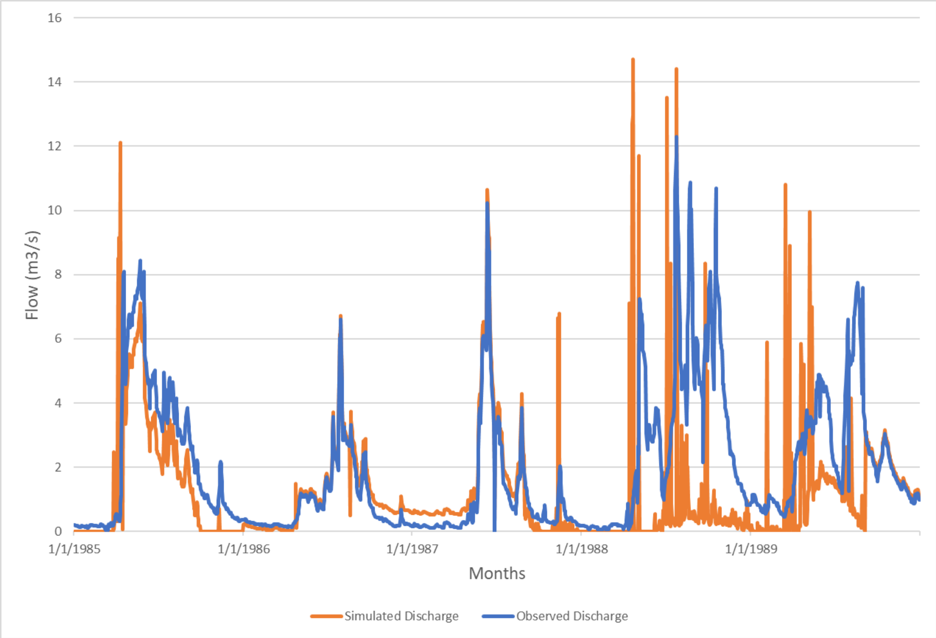


Figure 4.5 SWAT Model Validation Graphical Results

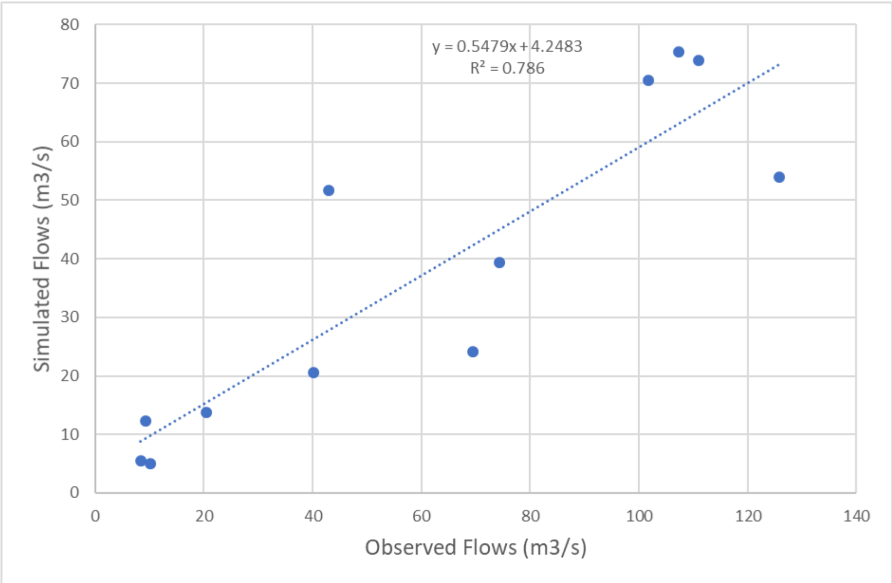


Figure 4.6 Scatter Plot for Validated SWAT Model Results

The R squared values for >95 and <5 percentile flows for the simulation period were determined to be 0.8612 and 0.638, respectively in the monthly scatter plot, as illustrated by Figures 4.7 and 4.8. The model was therefore noted to be a good estimator of high flows in comparison to low flows.

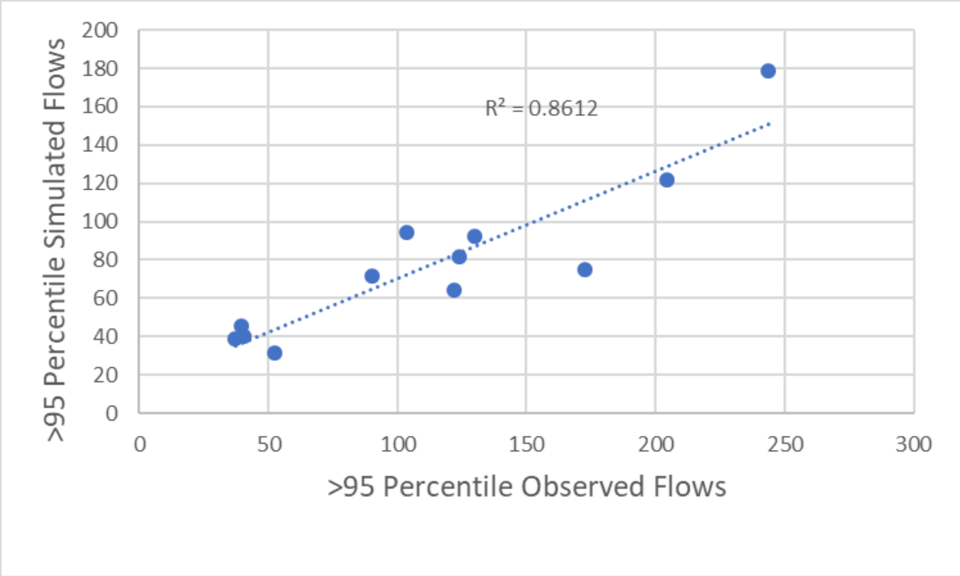


Figure 4.7 Scatter Plot for Simulated versus Observed Flows >95 percentile flows (1980–1989)

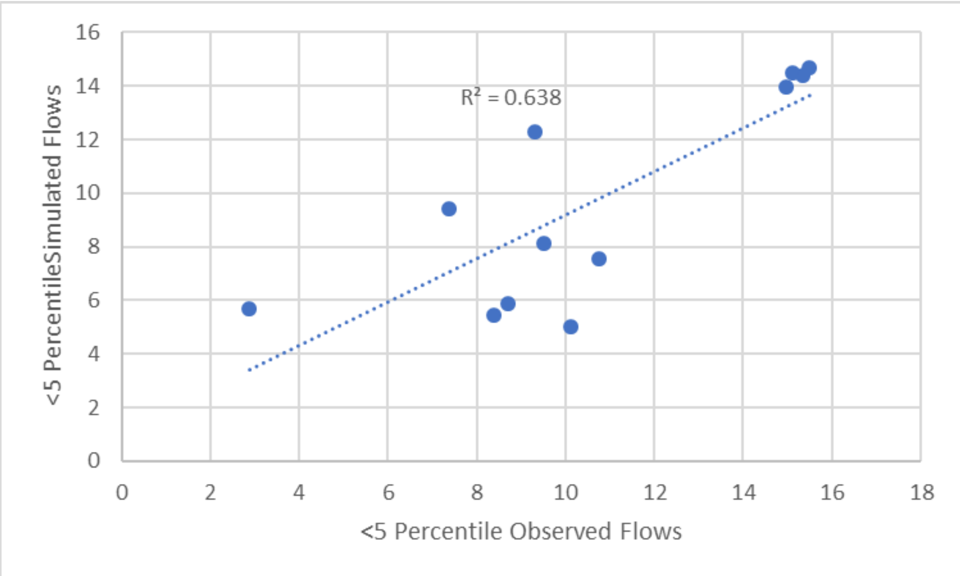


Figure 4.8 Scatter Plot for Simulated versus Observed Flows <5 percentile flows (1980–1989)

4.1.6 SWAT Model Performance Evaluation

The goodness of fit statistics which include the Coefficient of Determination (R^2), Bias, Nash and Sutcliffe Model Efficiency (NSE) were used to evaluate the performance of the SWAT model. The model statistical evaluation indices attained during calibration and validation periods for the SWAT model for both daily and monthly time steps are indicated in Table 4.3.

Table 4.3 Goodness of Fit Statistics for Calibration Period 1980-1984 and Validation Period 1985-1989

Goodness of fit Statistics	Calibration (1980-1984)	Validation (1985-1989)
R^2	0.854	0.786
NSE	0.822	0.815
Bias	0.392	0.381

4.2 Determination of the Impact of Land Use and Land Cover Changes in the Two Rivers Dam catchment

4.2.1 Land Use, Soil Type and Slope Definitions

The land use and soil maps were first loaded then followed by a lookup table for each map that was used to relate the default map classification with the SWAT crop database classification. After the land use and soil maps were added and clipped to the basin size and coverage, they were reclassified, and then overlaid. This resulted in the catchment's land use, soil and slope distribution as shown in Figures 4.9, 4.10 and 4.11. The land use definition indicated that the catchment has three major categories where Agricultural land covers 66.47% of the catchment area, Forest 26.80% and Range Grasses 6.73% of the area. The soil type definition showed that there are three major types of soil in the catchment including Haplic Ferralsol (26.17% of catchment area), Eutric Gleysol (14.36% of area) and Humic Nitisol (59.47% area) according to the soil data that was sourced from the Kenya Soil and Terrain (KENSOTER) database. The slope definition indicated that catchment 0-3% slope covered 16.28% of the catchment area, 3-7% slope (39.74% area), 7-12% slope (19.96% area) and 12-25% slope (22.32% area) and 25-99% slope (1.70% area).

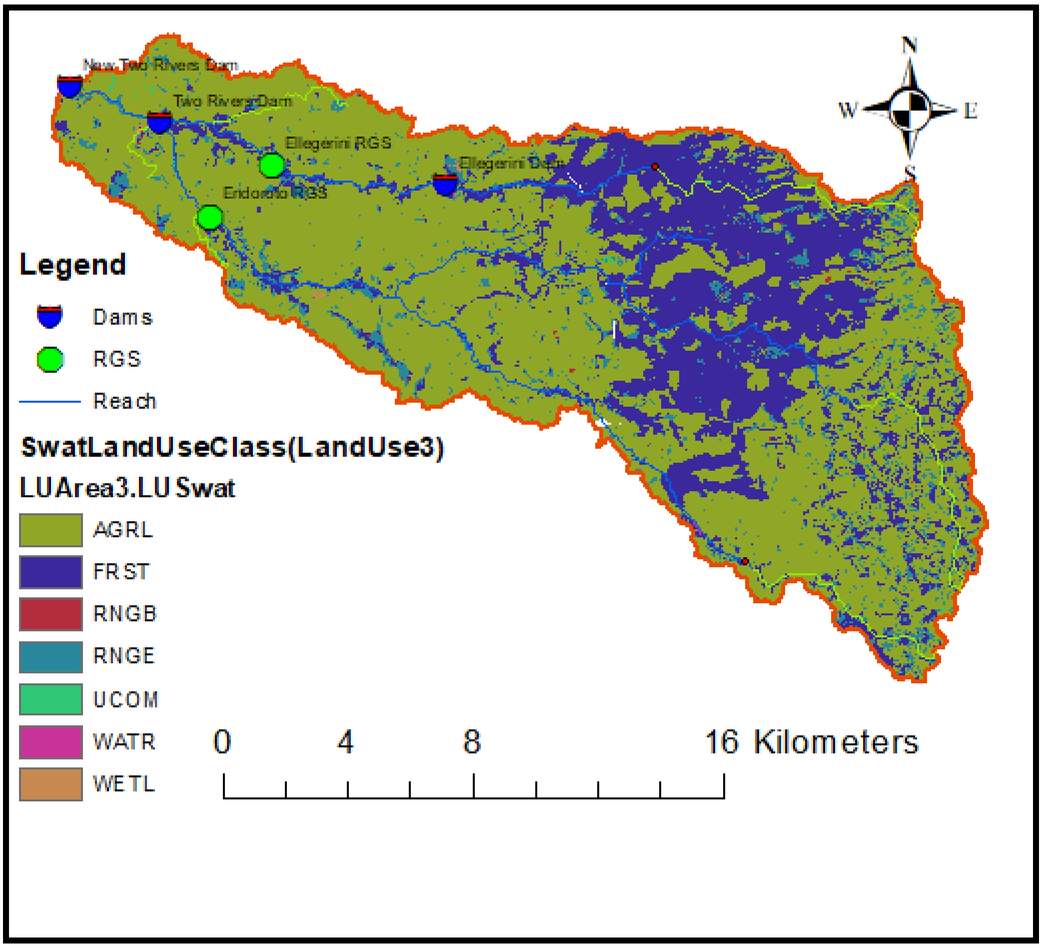
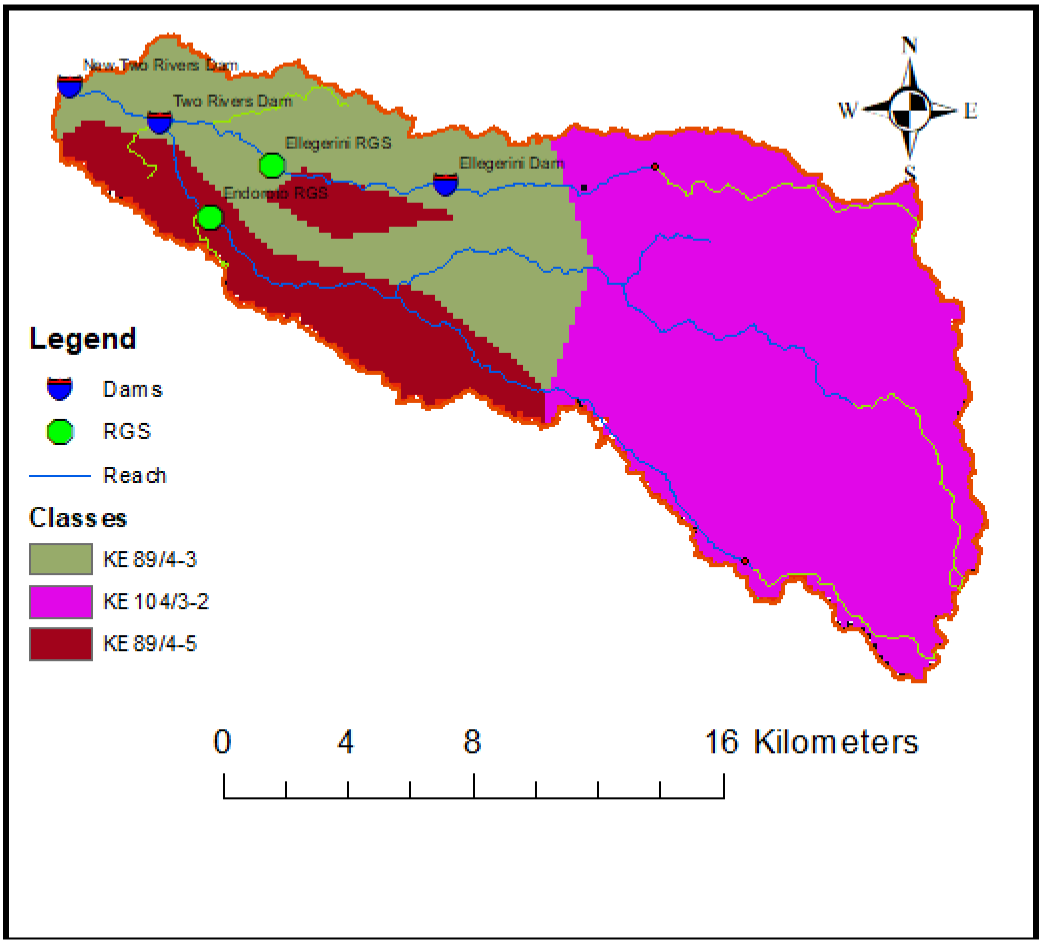


Figure 4.9 Land use class definition for the year 2016.



KEY
KE 89/4-3 – FRh – Haplic Ferralsol
KE 89/4-5 – GLe – Eutric Gleysol
KE 104/3-2 – NTu – Humic Nitisol

Figure 4.10 Soil class definition

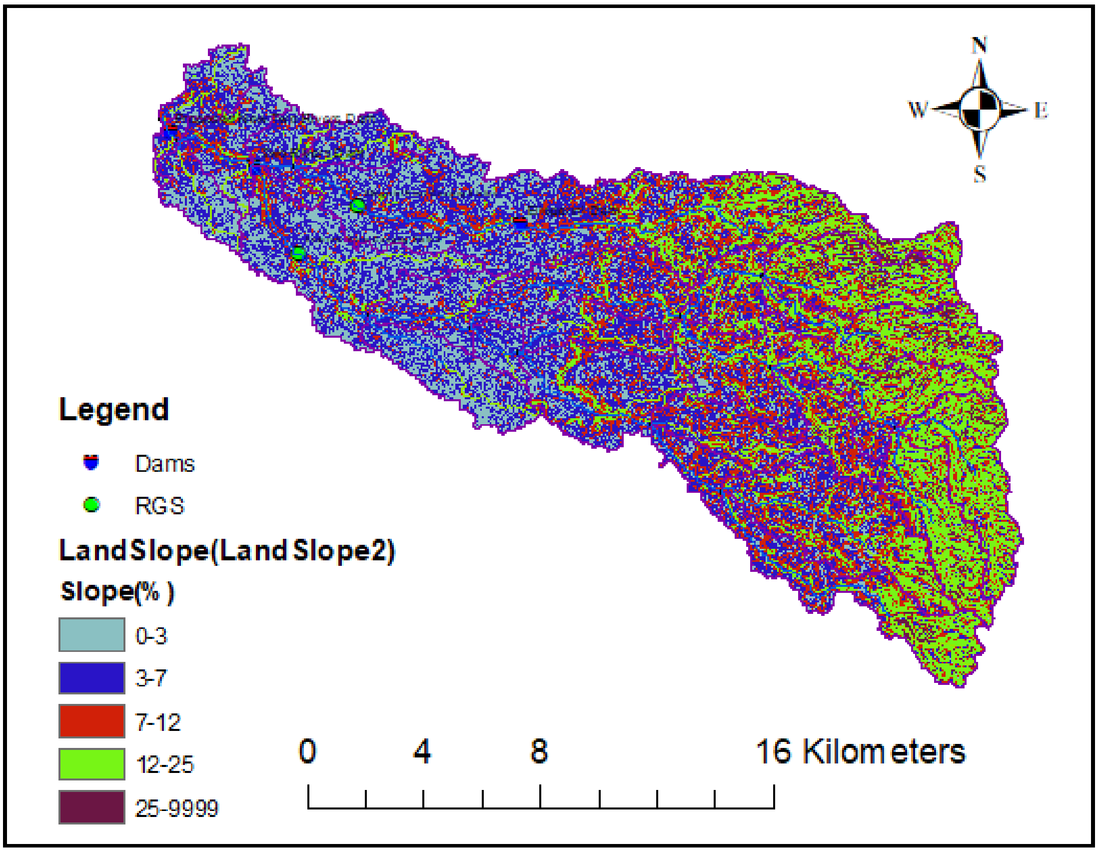


Figure 4.11 Slope Class Definition

4.2.2 Definition of HRUs

The definition of HRU's was achieved by defining threshold percentage areas below which the land use and soil types would be discarded. Here the land use threshold of 5%, a soils threshold of 5% and a slope threshold of 20% was selected. These values ensured that most land use and soil types in the watershed were represented fully in the semi distributed model. The Table 4.4 represents the land use soils and slope distribution created.

Table 4.4 Land Use, Soils and Slope distribution

Land use / Soils / Slope		Area [Ha]	% Area
Land Use	Range-Grasses --> RNGE	1894.9699	6.73
	Agricultural Land-Generic --> AGRL	18707.7553	66.47
	Forest-Mixed --> FRST	7542.9081	26.80
Soils	KE89/4-3	7365.6445	26.17
	KE89/4-5	4042.7999	14.36
	KE104/3-2	16737.1889	59.47
Slope	0-3	4582.1092	16.28
	3-7	11185.0713	39.74
	7-12	5617.8681	19.96
	12-25	6282.1058	22.32
	25-9999	478.4758	1.70

The simulation of the hydrological cycle of each HRU was based on the water balance including surfaces runoff, precipitation, percolation, interception, evapotranspiration, return flow from shallow aquifers and lateral flow from the soil profile (Gassman et al., 2007). There are two techniques for estimation of surface runoff in the SWAT model which are the Green & Ampt infiltration method and the Soil Conservation Service (SCS) curve number (USDA-SCS, 1972) method. The SCS CN method was used in the study. The study focused on the SCS-CN method because it utilizes daily rainfall data which was available for the study catchment. The SCS-CN method was created to simulate surface runoff occurring from the daily rainfall events.

The redistribution of water between the soil layers was calculated using the Sloan and Moore (1984) kinematic storage model. The contribution to stream flow is due to the lateral movement of water in the soil profile and percolation to the bottom of the profile which ultimately recharges the aquifer (Neitsch et al., 2009). The simulation of flows from the HRUs to the sub basin level are then routed using the Muskingum method of routing to the system of streams in the watershed. The SWAT technical manual provides a more detailed illustration of the calculation formulae used in the SWAT model.

4.2.3 Land Use Land Cover Change

The Two Rivers Dam catchment Landsat land cover land use satellite images at ten-year intervals for the past 31 years were downloaded from the USGS website and were chosen in the period December – February, which were the months that presented the least cloud cover thereby enhancing the quality of the satellite images. The images indicated the land cover change in the catchment from 1989 to 2020 as indicated in Figures 4.12, 4.13, 4.14 and 4.15. In the land use map legend, FRST means Forest, RNGB = Range Bush, RNGE = Range Grasses and AGRL = Agricultural Land according to the SWAT Theoretical Documentation by (Neistch S.L., 2011) and (Arnold, 1998).

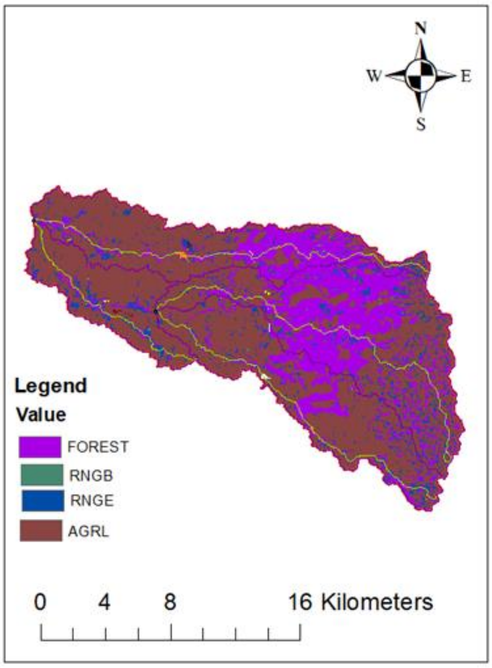


Figure 4.12 The 1989 catchment Land Use Map

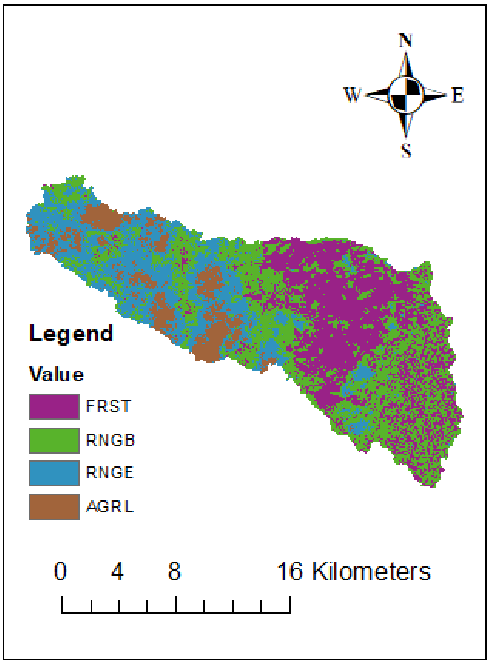


Figure 4.13 The 1999 catchment Land Use Map

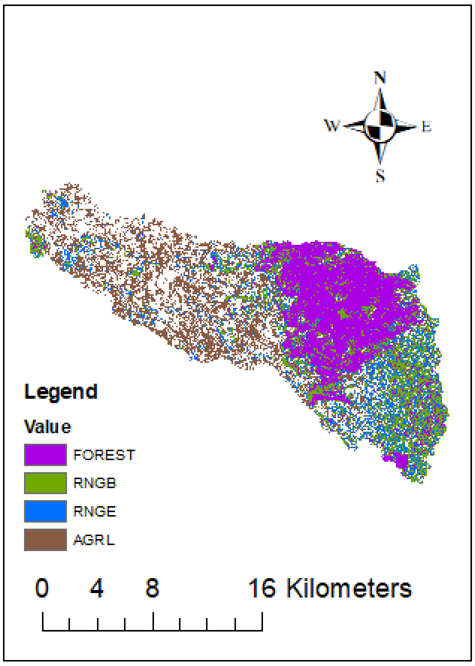


Figure 4.14 The 2009 catchment Land Use Map

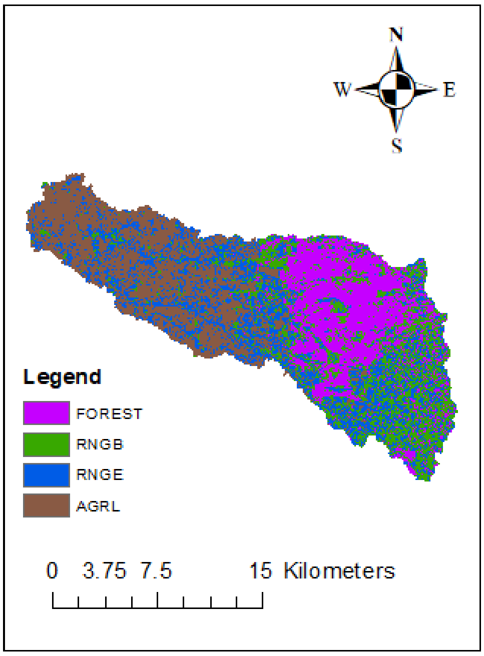


Figure 4.15 The 2020 catchment Land Use Map

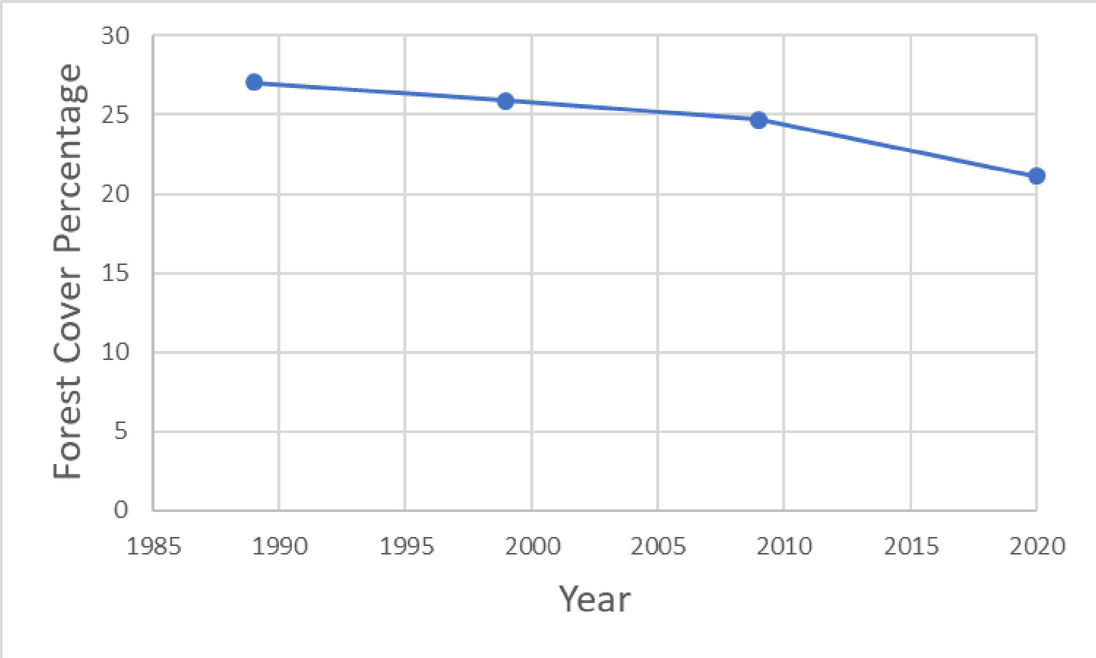


Figure 4.16 Percentage change of Forest Cover in Two Rivers Dam catchment from 1989 to 2020

The Land use land cover change from 1989 to 2020 at the 10-year intervals is evident (Figure 4.16). There has been significant reduction in the percentage of the catchment area covered by forest and a considerable increase in the percentage of the area covered by agricultural land. The percentage of land covered by forest in the catchment decreased from 27.05% in 1989 to 21.15% in 2020 (Figure 4.16). Additionally, the land covered by Agriculture increased from 15.52% in 1989 to 27.68% in 2020 as indicated in Table 4.5. Furthermore, annual runoff was observed in relation with the land use change and actual rainfall to increase over the years as indicated in Table 4.6 below where the runoff increased from 121.36 mm in 1989 to 167.32 mm in 2020. The land use change resulted in decreased baseflow from 94.52 mm in 1989 to 64.91mm in 2020 in the catchment as indicated in Table 4.7.

Table 4.5 Land Use Change Impact on the Runoff in the Catchment

Land Use Map	Forest (%)	Agricultural (%)	Runoff (mm)	Percentage Change in Runoff (%)
1989	27.05	15.52	121.36	-
1999	25.91	19.69	146.74	20.91
2009	24.68	21.06	158.21	30.36
2020	21.15	27.68	167.32	37.87

Table 4.6 Land Use Change Impact on the Baseflow in the Catchment

Land Use Map	Forest (%)	Agricultural (%)	Baseflow (mm)	Percentage Change in Runoff (%)
1989	27.05	15.52	94.52	-
1999	25.91	19.69	83.78	-11.36
2009	24.68	21.06	75.26	-10.17
2020	21.15	27.68	64.91	-13.75

4.2.4 Simulated Flows for Two Rivers Dam catchment with Land use Maps from 1989 to 2020

Different Land use maps of the Two Rivers Dam catchment between years 1989 to 2020 were added into the SWAT Model and the results are shown in Figure 4.17 below.

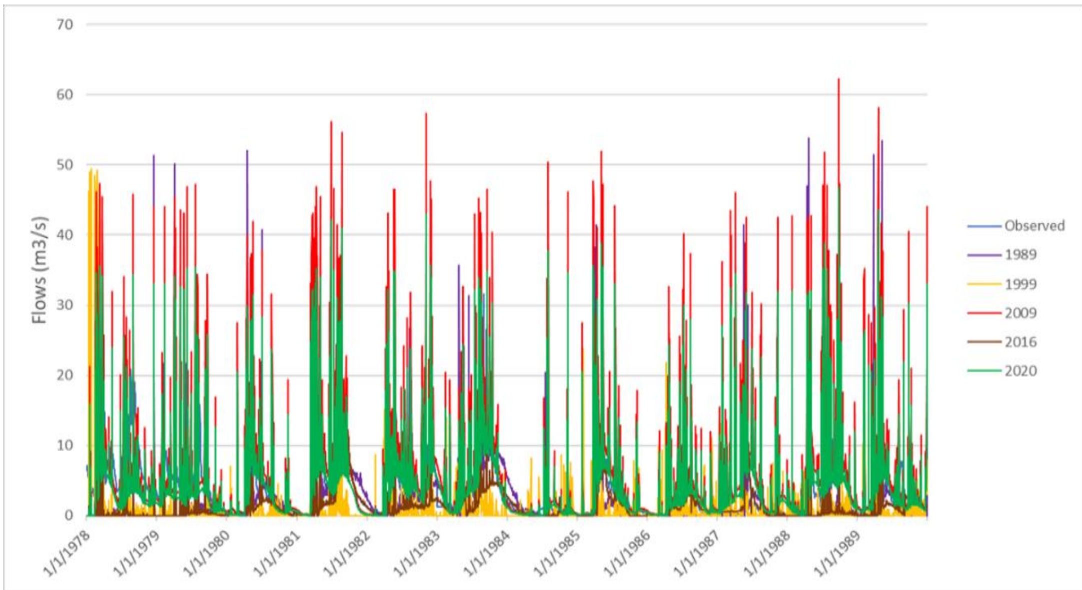


Figure 4.17 Simulated Flows for Two Rivers Dam Catchment with Land use Maps from 1989 to 2020

According to the above graph in Figure 4.17 there has been reducing flows at the outlet of the Two Rivers Dam catchment at the New Two Rivers dam over the 31-year period from 1989 to 2020.The results from Figure 4.17 and Table 4.6 indicate that there has been reducing flows at the Two Rivers Dam catchment outlet, i.e. at the New Two Rivers dam over the 31-year period from 1989 to 2020. The maximum flows reduced from 53.8m^3/s in 1989 to 44.19m^3/s in 2020. However, there was an increase in the flow in the year 2009. The determination of the coefficient of correlation of discharge with time i.e., the land use map (in the different years) with the respective discharge was calculated in Microsoft Excel as indicated in Figure 4.18. The coefficient of correlation was determined to be (r = -0.3926) as indicated in Figure 4.18. The coefficient of correlation, r is a number between negative one and one. r > 0 indicates a positive correlation. When r is less than 0, it shows a negative correlation. Values of r near zero show a linear relationship that is very weak. Therefore, coefficient of correlation which was determined to be (r = -0.3926), indicates a negative correlation of discharge with time.

Table 4.7 Land Use Change Maximum and Minimum Flows

Land Use Map	Maximum Flows (m^3/s)	Minimum Flows (m^3/s))
1989	53.8	0
1999	49.4	0
2009	62.3	0
2016	46.73	0
2020	44.19	0

Land Use Map Year	Maximum Flows (m3/s)
1989	53.8
1999	49.4
2009	62.3
2016	46.73
2020	44.19

	Land Use Map Year	*Maximum Flows (m3/s)*
Land Use Map Year	1	**-0.392585933**
Maximum Flows (m3/s)	**-0.392585933**	1

r=	**-0.392585933**

Figure 4.18 Coefficient of Correlation of Discharge with Time

4.2.5 SWAT Model Scenario Analysis Results

SWAT scenario analysis was conducted where the forest cover of the land use of the year 2020 which is the latest study year (thereby simulating current conditions as opposed to past conditions) by 5% progressively. The impact of the increased forest cover was then analyzed in relation to the runoff and the baseflow. The results of the impact of increased forest cover on the runoff and baseflow are summarized in Table 4.8.

Table 4.8 Impact of Increased Forest Cover on the Runoff and Baseflow in the Catchment

Forest (%)	Runoff (mm)	Baseflow(mm)	Percentage Change in Runoff (%)	Percentage Change in Baseflow (%)
21.15	167.32	64.91	-	-
26.15	165.64	66.87	-0.97	3.01
31.15	163.75	69.06	-1.15	3.28
36.15	161.61	71.42	-1.31	3.41

The results in Table 4.8 indicate that increasing the forest cover of the land use year of 2020 which is the latest study year (thereby simulating current conditions as opposed to past conditions) progressively by 5% decreases the resulting runoff and increases the baseflow. The forested areas therefore need to be properly conserved and in certain areas reforested to increase the forest cover thereby contributing to restoration of the hydrological function of the catchment.

4.3 The Development, Calibration and Validation of the WEAP Model

4.3.1 WEAP Model Setup

The schematic representations of the Kapatgat catchment system in the WEAP model are shown in Figures 4.19 and 4.20. The WEAP schematic representations consist of four demand sites denoted by the red circles (nodes) which include domestic, commercial, agricultural and industrial water demand sites. Additionally, the representations consist of three water supply sources represented by the green triangles which include; the proposed New Two Rivers Dam, the existing Two Rivers Dam and the Ellegerini Dam as indicated in Figure 4.19. Transmission links denoted by the green lines connect the demand sites. The outflows of the wastewater from the demand sites are denoted by return flow links which are shown by the red lines that lead to the receiving body which is river Sosiani (the blue line) as indicated in Figure 4.20. The two river gauging stations in the Two Rivers Dam catchment system which are the Ellegerini and Endoroto river gauging stations are denoted by the blue circles. The Kapagat forest (denoted by the green circle) and the three water treatment plants in the catchment which include the Naiberi, Sosiani and Kapsoya water treatment plants are denoted by the green diamond shapes. The rivers in the catchment which include the Sosiani, Ellegerini and Endoroto rivers are denoted by the light blue lines as indicated in Figure 4.20.

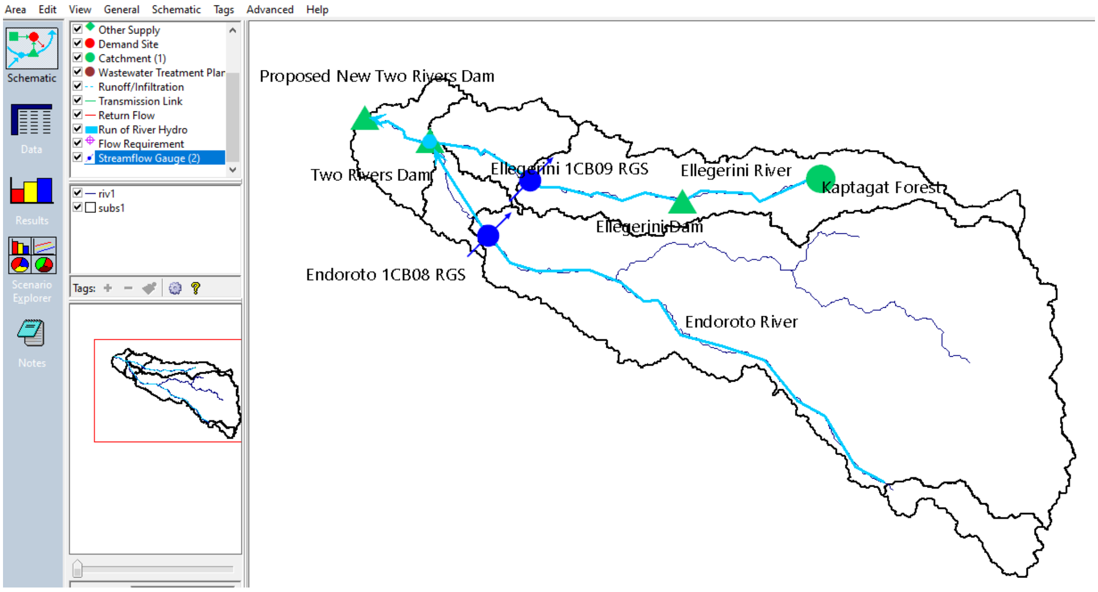


Figure 4.19 Schematic presentation of the Two Rivers Dam catchment

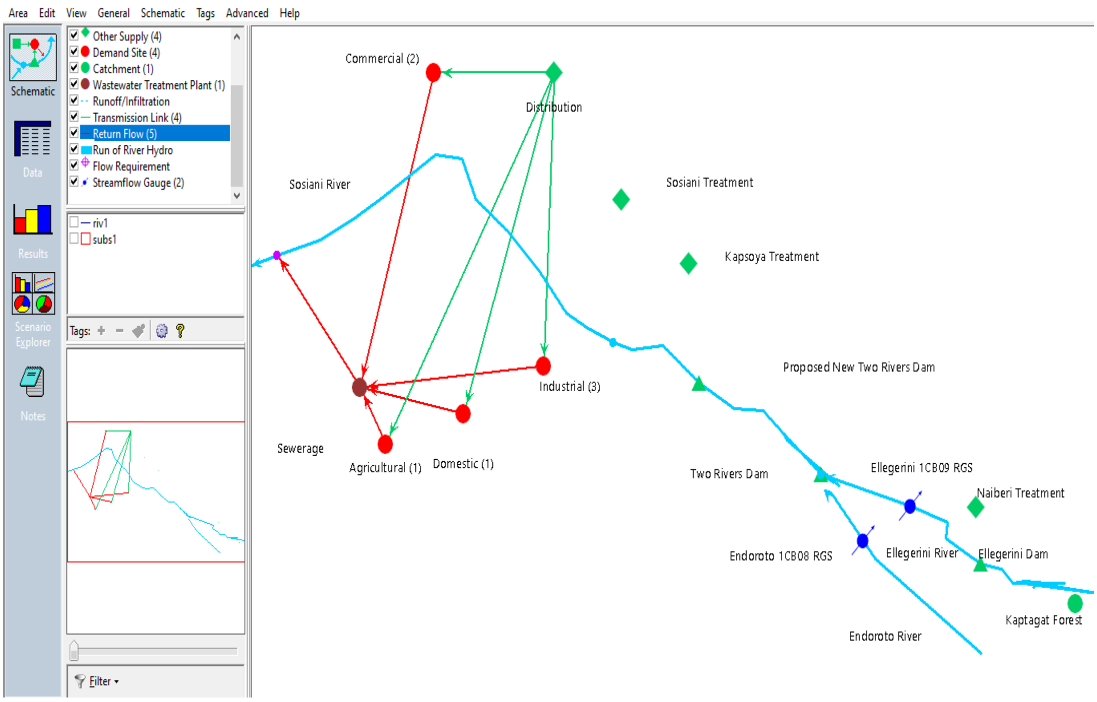


Figure 4.20 Schematic presentation of the Two Rivers Dam catchment system and demands in WEAP

4.3.2 Modelling Water Demand

The WEAP model that was created consisted of four demand sites i.e., domestic demand, agricultural demand, industrial demand and commercial demand (nodes).

Five major water use sectors that were simulated in the WEAP model were as follows:

1. Domestic water demand and institutions e.g., Schools, households and healthcare.
2. Agricultural Water Demand
3. Commercial demand. e.g., Business premises and hotels in Eldoret town.
4. Industrial Demand e.g., Rivatex, Raiply and Kenknit
5. Environmental flows

4.3.2.1 Domestic Water Demand

Water allocation priorities: Competing water demand sites are allocated water in accordance with their respective priorities of water demand. The use of priorities is crucial during water scarcity periods because it enables the satisfaction of the higher priority water demand site needs while ensures later consideration of lower water demand priority sites. The linear programming method in WEAP solves the water allocation problems in the model as it classifies the water priorities from 1 to 99. The highest priority of water demand node is denoted by 1 and the lowest priority water demand node is represented by 99. An approach where demand priority and preference is used which is a robust technique and provides an effective algorithm to solve water allocation challenges within a river basin. The water allocation problems in the model are solved using the linear programming heuristic in WEAP that maximizes satisfaction of water demand needs in relation to supply priorities, mass balances and demand site preferences among other constraints (Purkey et al., 2008). Table 4.9 shows the modeled priority demand sites as used in the WEAP model.

Table 4.9 Priorities on Water Allocation

Demand	Priority
Domestic and Institutions	1
In stream flow requirements (Environmental flows)	1
Commercial	2
Industrial	3
Other uses	4
Reservoir	9

Data on the quantity of domestic water demand was collected from ELDOWAS and is indicated in Figure 4.21 below. The data is also shown in Appendix I.

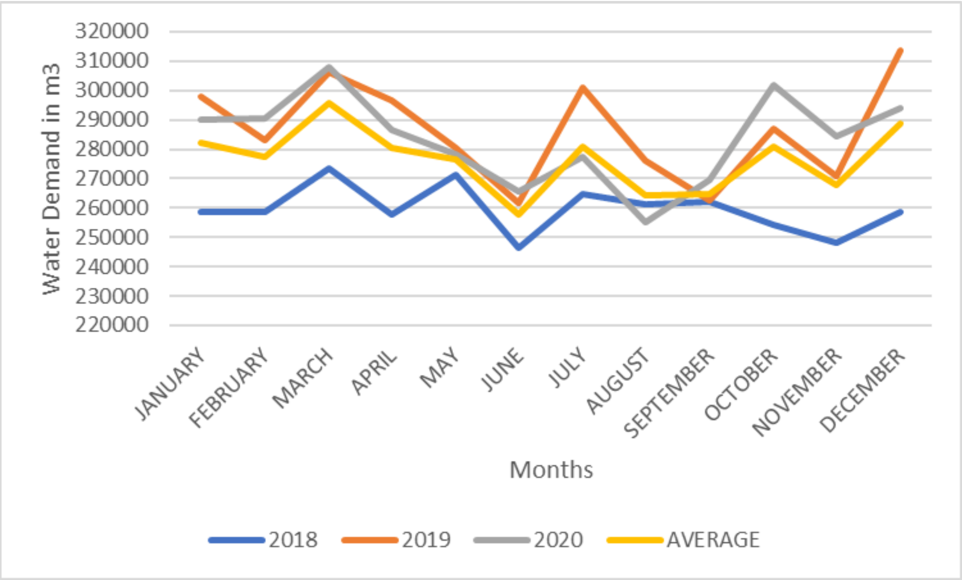


Figure 4.21 Domestic Water Demand in m^3 in Two Rivers Dam catchment

4.3.2.2 Agricultural Water Demand

Data on the quantity of agricultural water demand was collected from ELDOWAS and is indicated in Figure 4.22 below. The data is also shown in Appendix IV.

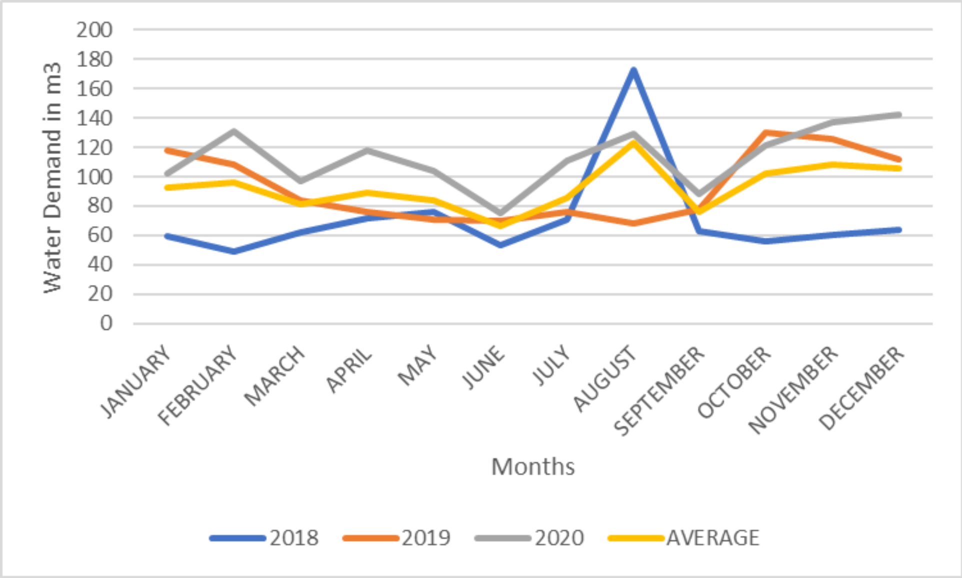


Figure 4.22 Agricultural Water Demand in m^3 in Two Rivers Dam catchment

4.3.2.3 Commercial Water Demand

Data on the quantity of commercial water demand was collected from ELDOWAS and is indicated in Figure 4.23 below. The data is also shown in Appendix II.

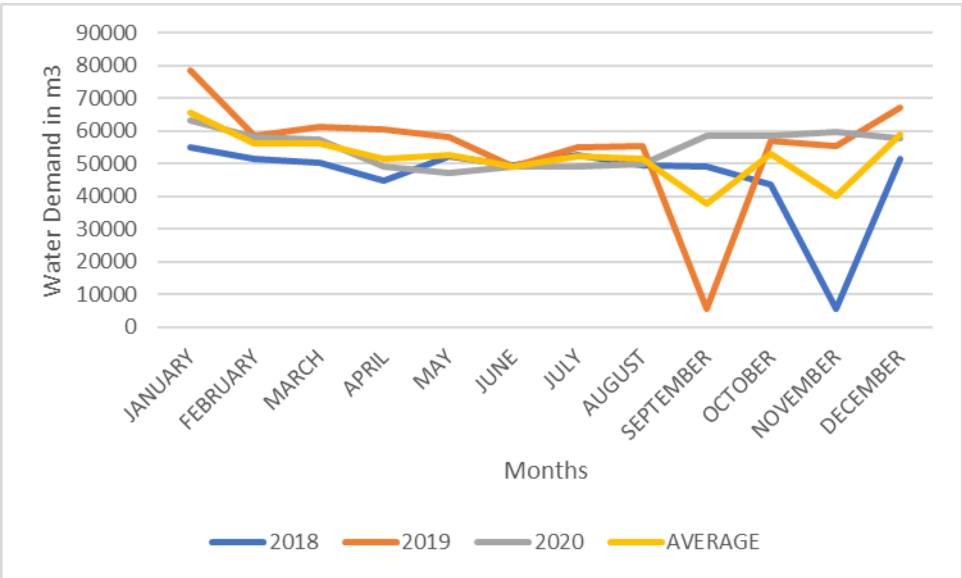


Figure 4.23 Commercial Water Demand in m^3 in Two Rivers Dam catchment

4.3.2.4 Industrial Water Demand

Data on the quantity of industrial water demand was collected from ELDOWAS and is indicated in Figure 4.24 below. The data is also shown in Appendix III.

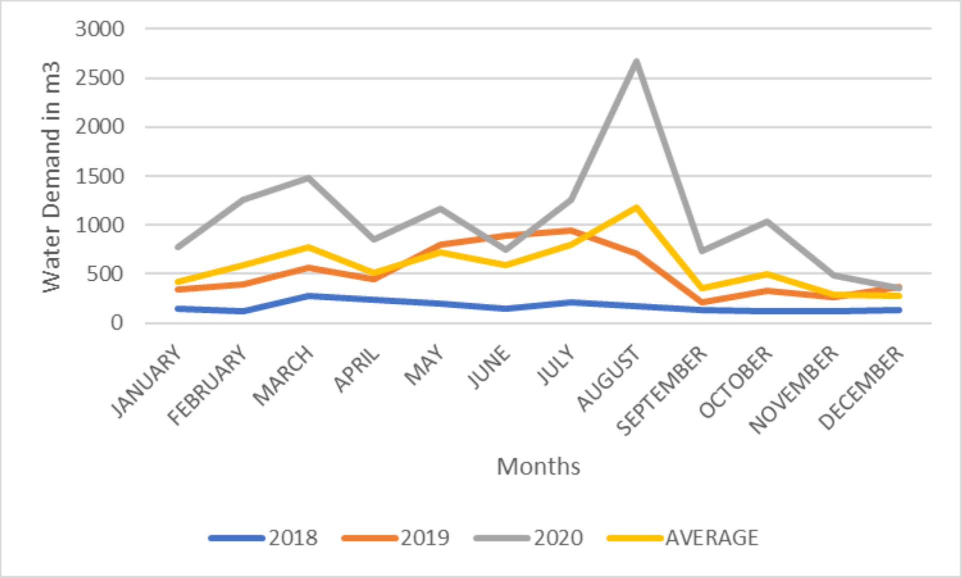


Figure 4.24 Industrial Water Demand in m^3 in Two Rivers Dam catchment

4.3.3 Modelling Water Supply

4.3.3.1 Water Supply from Treatment Works

Data on the quantity of water supply from Kapsoya, Sosiani and Naiberi Treatment Works i.e, Water Supplied from Two Rivers and Ellegerini Reservoirs was collected from ELDOWAS and is indicated in Figure 4.25 below. The data is also shown in Appendix V.

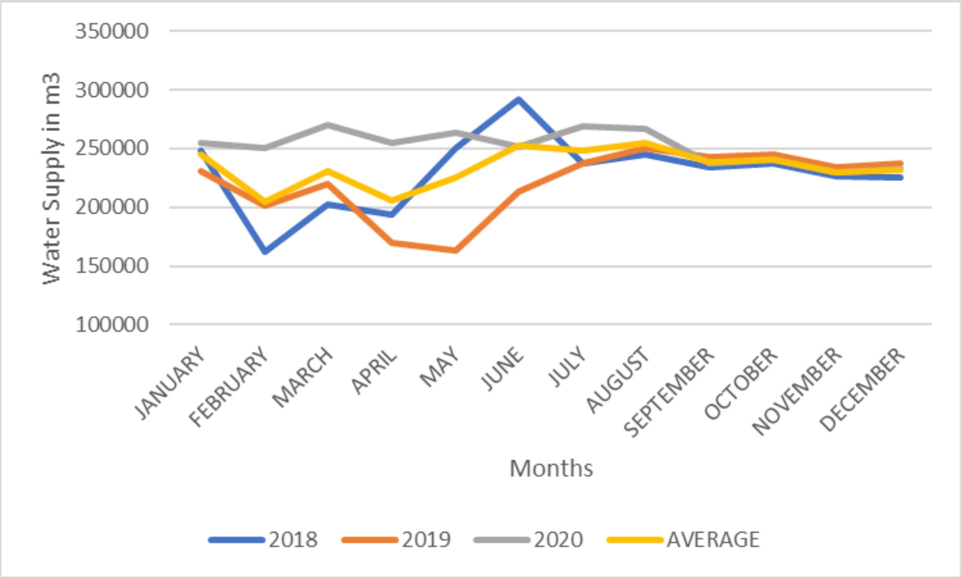


Figure 4.25 Water Supply in m^3 from Two Rivers and Ellegerini Reservoirs

4.3.4 Unaccounted For Water

Data on the Unaccounted-for Water (UFW) in percentages was collected from ELDOWAS and is indicated in Figure 4.26 below. The data is also shown in Appendix VI.

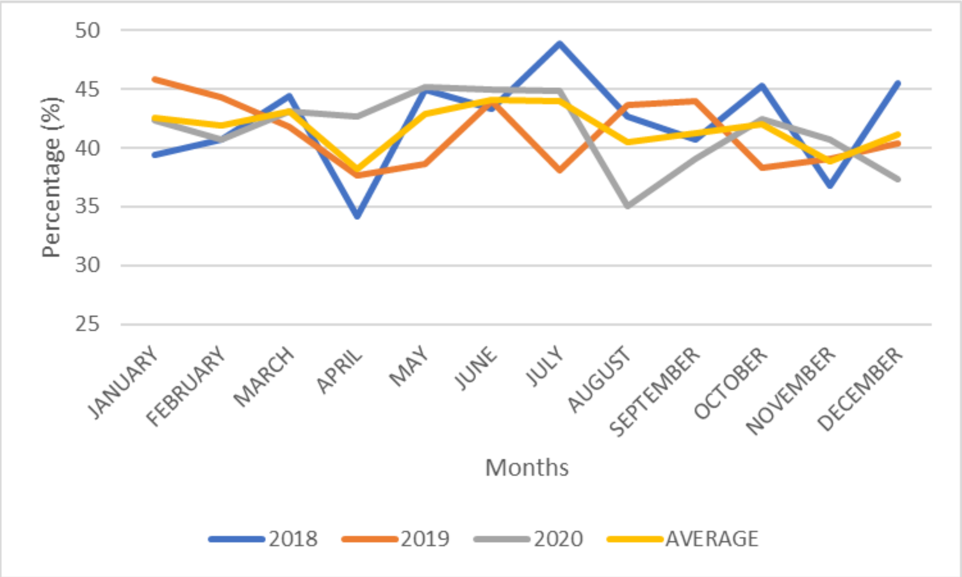


Figure 4.26 Unaccounted for Water (UFW) in Percentages

4.3.5 Water Demand and Population

In 2009, the municipality of Eldoret had a water demand estimated at 26,000 m3/d. This has grown to around 60,000 m3/d in 2019 reflecting the dramatic growth in the town population and commercial activity. Eldoret town has an intercensal population growth rate is 3.7% p.a (MIBP 2018).

4.3.6 Calibration and Validation results of the Model

Water supply and water demand modeling was conducted using WEAP model and then the model was calibrated and validated. Calibration of WEAP model was done based on water demand and water supply. The calibration period of the model was taken to be the year 2019 and validation period was the year 2020. The scenarios analyzed include; The Reference Scenario; The Infrastructural Development Scenario and the Population Growth Scenario.

Comparison between the water demand in Eldoret town simulated with WEAP model and the actual water demand goodness of fit is shown in Figures 4.27 and 4.28 The performance of the model is assessed using standard statistics; mean error (ME), mean square error (MSE) and model coefficient of efficiency (EF).

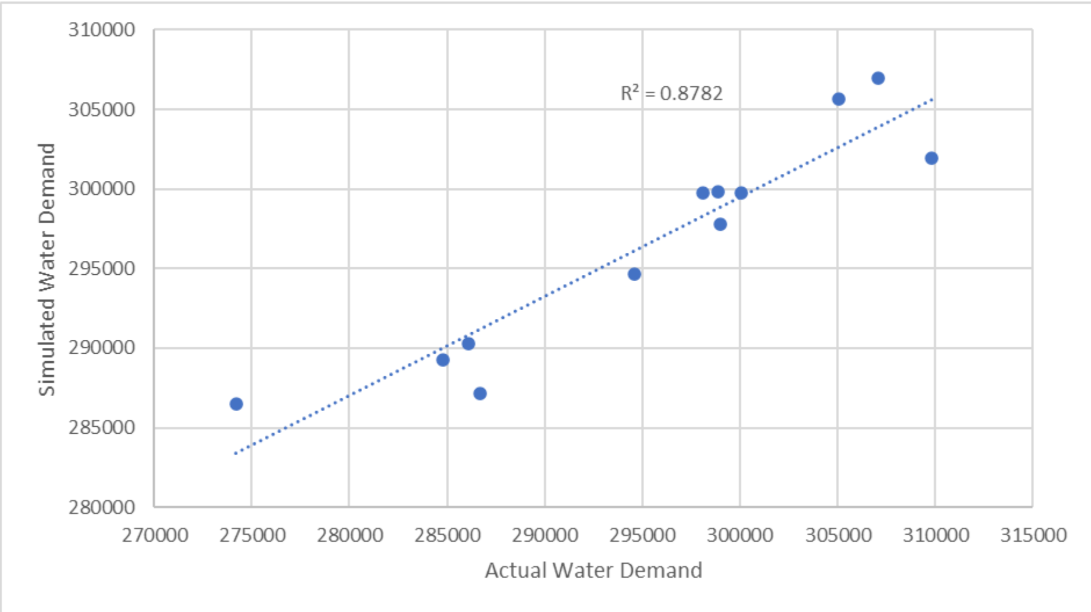


Figure 4.27 Calibration of the 2019 Actual and Simulated Water Demand

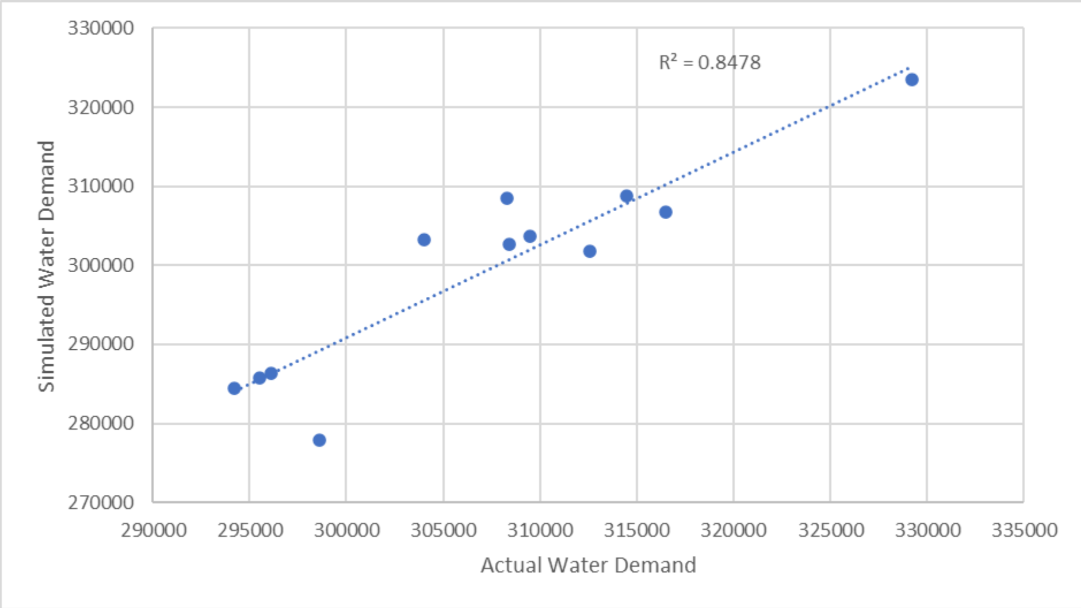


Figure 4.28 Validation of the 2020 Actual and Simulated Water Demand

A scatter plot diagram of observed and simulated results was drawn and the regression line indicated as shown in Figures 4.27 and 4.28. During the calibration period in the year 2019 R^2 for the actual and simulated water demand was found to be 0.88 while during the validation period in 2020 the R^2 was found to be 0.85 as shown in the above monthly scatter plots. The results indicate that the model simulates the observed conditions reasonably well. Summary of statistical analysis performed between actual and simulated water demand is shown in Table 4.10.

Table 4.10: Statistical analysis of the performance of water demand in Eldoret demand point

	ME	MSE	R^2	EF
Simulation (2019)	-40498	5.56E+08	0.88	0.84
Simulation (2020)	-54100	7.07E+09	0.85	0.82
Range	≤ 0	≤ 0	0 - 1	$-\infty - 1$

ME: mean error; MSE: relative mean root square error; EF: model efficiency; R^2 goodness of fit.

The mean square error (MSE) and the mean error (ME) have a minimum value of 0.00. Zero value for these parameters show that the model is perfect and has good prediction capability. Also the ME and MSE reflect the bias or systematic deviation in the model results and the random error after correction. The model efficiency (EF) and goodness of fit (R^2) have a maximum value of 1.00. R^2 values close to 1.00 indicate better prediction capability of the model. The efficiency coefficient EF of the model is a scaled and dimensionless version of the MSE which ranges between zero and one (zero or one for a perfect model) shows a clearer assessment of the performance and results of the model. The analysis was done as shown in Table 4.8 where the EF for the water demand and simulated water demand ranges from 0.82 to 0.84. According to the values of the statistical parameters obtained, WEAP model simulates water supply and water demand with acceptable accuracy.

4.4 Application of the WEAP Model in Analyses of Management and Infrastructural Development Scenarios

WEAP was applied to evaluate all the proposed scenarios and recommended management options. The scenarios analyzed include; The Reference Scenario; The Infrastructural Development Scenario and the Population Growth Scenario. A summary of the results is provided in Figures 4.29, 4.30, 4.31, 4.32 and 4.33. WEAP provides the results in charts, that include all demand sites including all users: schools, residential, institutions health care centers.

The management options applied to the Two Rivers Dam catchment WEAP Model include;

- Increased Groundwater Use
- Reduction of Unaccounted for Water from 41% to 15%
- Increased Rainwater Harvesting
- Increased Water use Efficiency

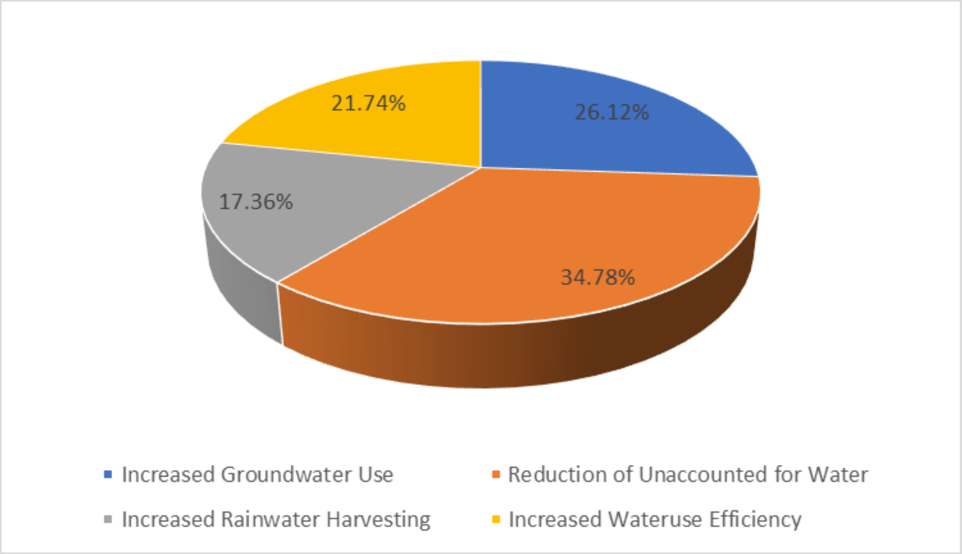


Figure 4.29 The impact of the management options on the Reference scenario

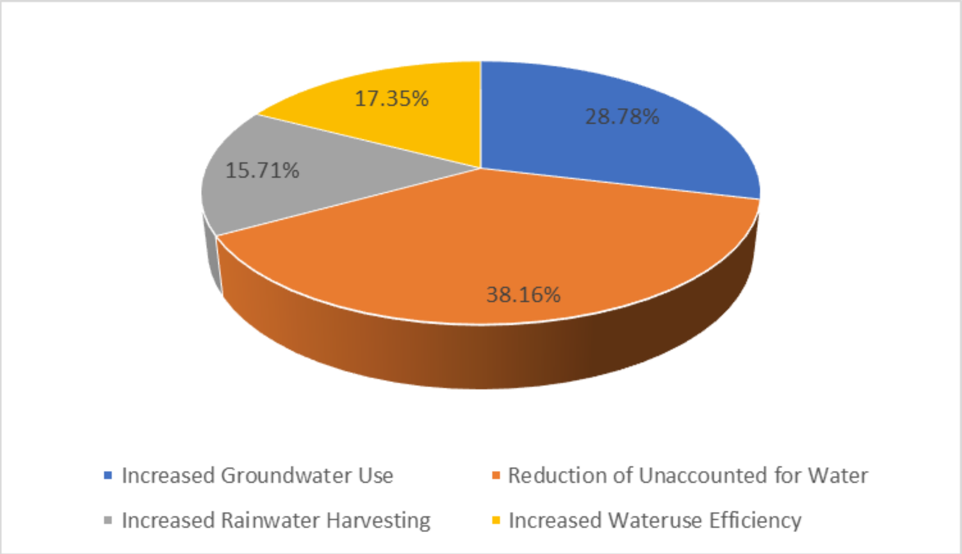


Figure 4.30 The impact of the management options on the Infrastructural Development Scenario

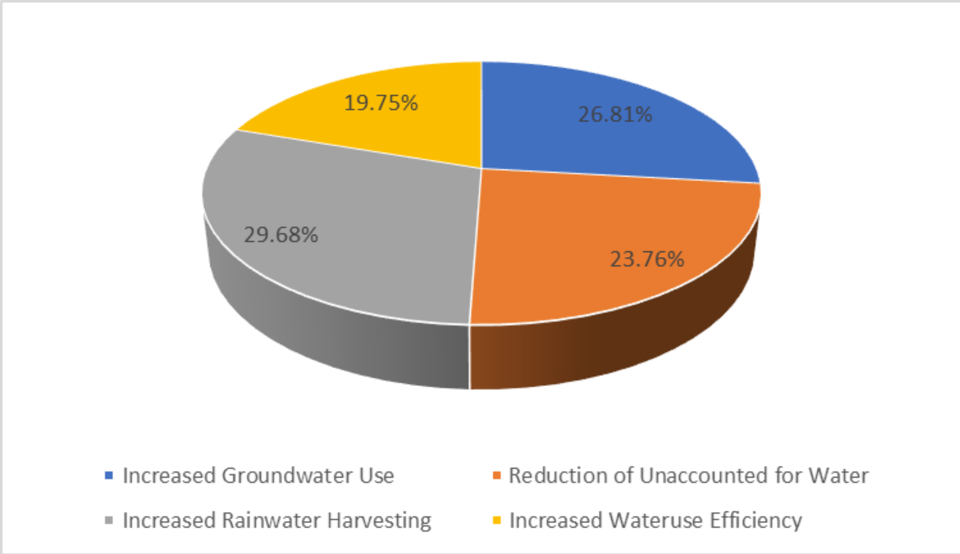


Figure 4.31 The impact of the management options on the Population Growth Scenario

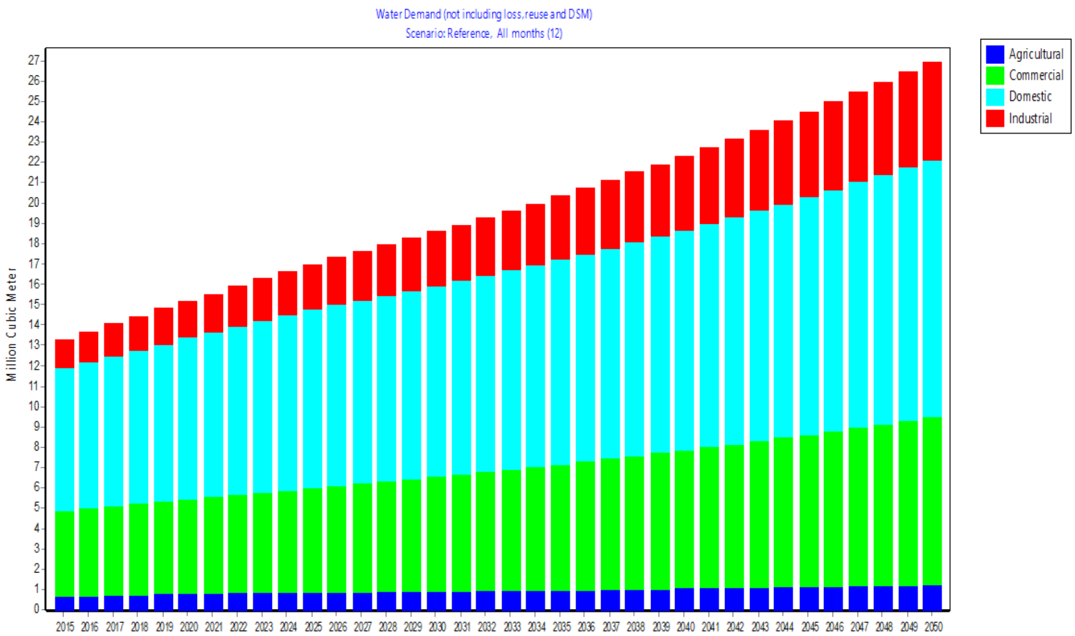


Figure 4.32: Projected water demand when using the reference scenario

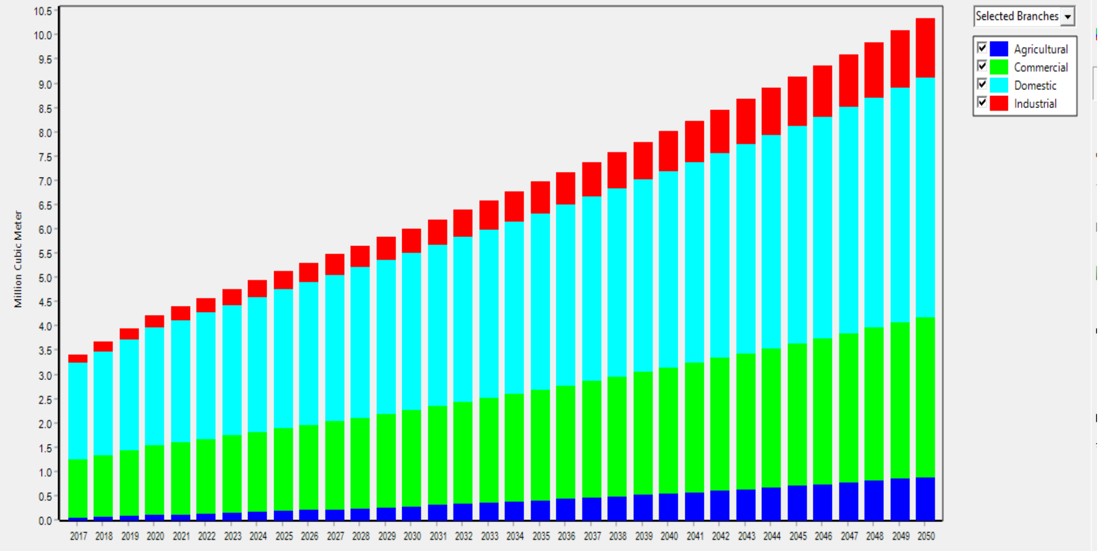


Figure 4.33: Projected unmet water demand when using the reference scenario

4.4.1 Discussion of Scenario Analysis Results

4.4.1.1 Reference Scenario

The WEAP model estimates the unmet water demand and water demand at each demand point in relation to the water supplied to every demand node in consideration of the demand priority and then adds the unmet water demand or water demand for all the points annually. The reference scenario WEAP results show that the projected total water demand will increase by a factor of two from 13.14 M m^3 in 2015 to 26.71 M m^3 by the end of 2050 as indicated in Figure 4.32. Additionally, the projected unmet demand will increase by a factor of three from 3.68 M m^3 to 10.07 M m^3 over the same period as indicated in Figure 4.33. The management option that had the most impact on the reference scenario was the reduction of unaccounted for water while the one with least impact was through increased rainwater harvesting.

4.4.1.2 Infrastructural Development Scenario

The scenario involved the proposed water resource development strategies to meet the water demand of Eldoret. The infrastructural development scenario entailed the construction of the Proposed New Two Rivers Dam (700 meters downstream of the existing Two Rivers Dam) and its capacities over the various periods indicated in Table 4.12. The infrastructural development in the catchment improved the demand coverage in the catchment by 39.4%.

The scenario's results indicate that the water supply capacity of Eldoret will increase from 36,400m3/d in 2015 to a 93,900 m3/d in 2050. The management option that had the most impact on the infrastructural development scenario was the reduction of unaccounted for water while the one with the least impact was through increased rainwater harvesting. The total water demand increased from 54,951 m^3/d in 2015 to 159,788 m3/d in 2050 as shown in Table 4.9 and Figure 4.34 which indicates that the construction of the proposed New Two Rivers Reservoir will not be adequate to fully satisfy the rising water demand in the catchment.

Table 4.11 The Proposed Infrastructural Development Capacities in Two Rivers Dam catchment

Infrastructural Development Scenario	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Existing development capacity (m3/d)	36,400	36,400	36,400	36,400	36,400	36,400	36,400	36,400
Construction of New Two Rivers Dam (m3/d)	0	0	28,750	28,750	57,500	57,500	57,500	57,500
New Capacity After Construction of New Two Rivers Dam (m3/d)	36,400	36,400	65,150	65,150	93,900	93,900	93,900	93,900
Total Water Demand (m3/d)	54,951	61,277	72,915	86,365	101,694	118,908	138,432	159,788
Deficit surplus based on existing sources (2017) (m^3/d)	**-18,551**	**-24,877**	**-7,716**	**-18,215**	**-7794**	**-25,008**	**-44,532**	**-65,888**

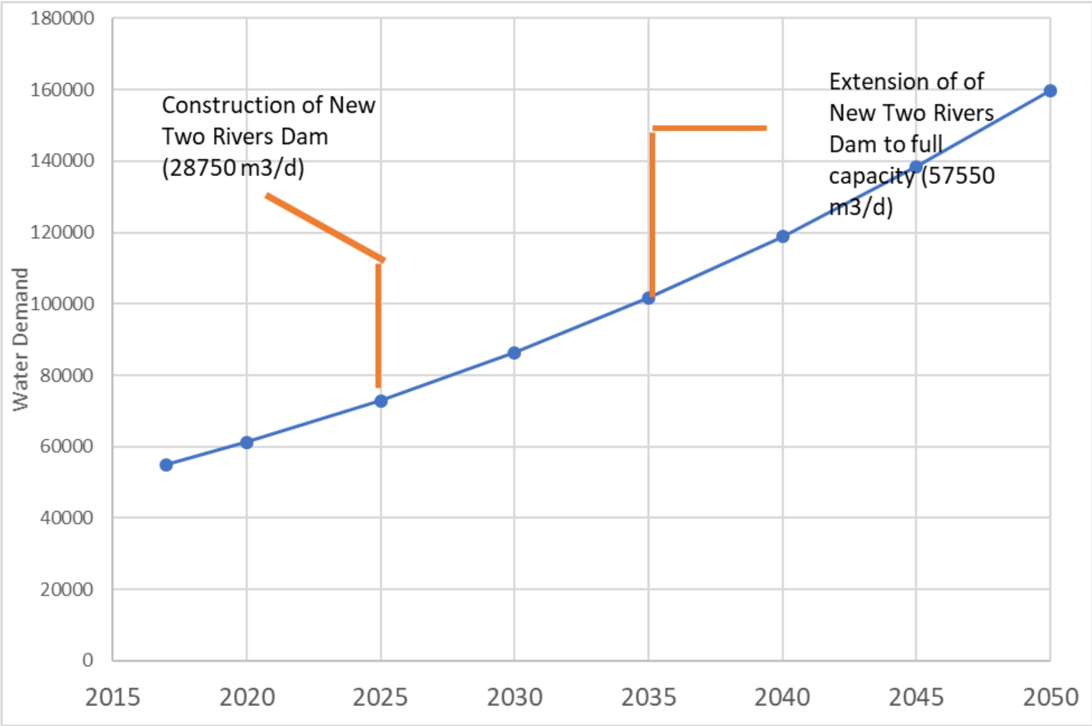


Figure 4.34: Water demand with Infrastructural development in Two Rivers Dam catchment

4.4.1.3 Population Growth Scenario

The population growth scenario entailed increasing the population from the normal average intercensal population growth rate of 3.7 % to 6%. The WEAP results indicate that the management option that had the most impact on the population growth scenario was increased rainwater harvesting, while the one with the least impact was through increased water use efficiency.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

The following are the main conclusions and recommendations of the study:

5.1 Conclusions

The poor availability of observed accurate stream flow data was a hindrance to accurate calibration and validation of simulated stream flow. However, the availability of adequate and accurate land use, climate, and flow data enabled the proper model setup and comprehension of the hydrology of the Two Rivers Dam catchment. The SWAT model was successfully calibrated and the goodness of fit statistics which include the Coefficient of Determination (R^2), Bias, Nash and Sutcliffe Model Efficiency (NSE) were used to evaluate the performance of the SWAT model. The SWAT model statistical evaluation indices attained during the calibration period are R^2 0.854, NSE 0.822 and Bias 0.392. Additionally, for the validation period the R^2 was 0.786, NSE 0.815 and Bias 0.381. The WEAP model results for the actual and simulated water demand in the calibration period of 2019 the R^2 was 0.88 while during the validation period in the year 2020 the R^2 was 0.85. The results of the model simulation indicated that the management option that had the most impact on all the scenarios was the reduction of unaccounted for water while the one with the least impact was increased water use efficiency. The main objective of this study was to develop SWAT and WEAP models for the sustainable water resources management of the Two Rivers Dam catchment. The following conclusions were drawn from the study:

1. The SWAT model was able to effectively generate simulated river flows draining to the Two Rivers and Ellegerini Reservoirs as an input to the WEAP model as shown by the good calibration and validation results.

2. The SWAT model results indicate that the land use change resulted in increased surface runoff and decreased baseflow in the catchment.
3. The WEAP model was able to effectively simulate the water supply and demand of the Two Rivers Dam catchment. The calibration and validation results showed that the results of the model were reasonably good, and thus the model was well adapted to the study. The WEAP model can therefore be used to effectively manage water resources with regards to water balance and can therefore assist the relevant stakeholders in decision-making.
4. The infrastructural development in the catchment improves the demand water coverage in the catchment by 39.4%.
5. The unmet water demand will continue to increase over the coming years mainly due to the rapid population growth, and if the available water resources that are already limited remain the same and there is no new water infrastructure development in the catchment.
6. The WEAP model was able to show that the catchment cannot be able to perform well with additional demands. It predicted that the proposed New Two Rivers Reservoir will not be sufficient to fully satisfy the rising water demand in the catchment as from the year 2040, if there is no new water infrastructure development in the catchment.

5.2 Recommendations

The study recommends the following;

1. The forested areas need to be properly conserved and in certain areas reforested to restore the hydrological function of the catchment.
2. The Water Resources Authority (WRA) should install and maintain more river gauging stations in the catchment to improve on the data recording in the catchment. The model will be able to perform better with more data availability from both the water supply and water demand sides. More accurate data recording will enhance accuracy in water demand management and water allocation.
3. The scenarios in the study can bring about a discussion among the catchment's water stakeholders involved in water management in the watershed which will ensure better comprehension of the various water problems in the catchment.
4. Due to the deterioration of water infrastructure which results in water leakage, rehabilitation of the dilapidated infrastructure including the water retaining structures and the water transmission lines is highly recommended.

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APPENDICES

Appendix I: The Domestic Water Demand in m^3 for Two Rivers Dam catchment

	2018	2019	2020	AVERAGE
JANUARY	258613	297760	289829	282068
FEBRUARY	258599	283165	290334	277366
MARCH	273660	306357	307797	295938
APRIL	257637	296671	286423	280243
MAY	271064	280277	278091	276477
JUNE	246238	261478	265535	257751
JULY	264765	300897	277546	281069
AUGUST	261263	276290	255075	264209
SEPTEMBER	262134	262578	269701	264804
OCTOBER	254211	286848	301764	280941
NOVEMBER	248198	270760	284208	267722
DECEMBER	258605	313531	293779	288638

Appendix II: The Commercial Water Demand in m^3 for Two Rivers Dam catchment

	2018	2019	2020	AVERAGE
JANUARY	55202	78519	63249	65656
FEBRUARY	51317	58753	58001	56024
MARCH	50294	61159	57497	56317
APRIL	44776	60655	49191	51541
MAY	52174	58351	47344	52623
JUNE	49487	49294	48991	49257
JULY	52629	54964	49038	52211
AUGUST	49453	55260	49771	51495
SEPTEMBER	49094	5395	58367	37619
OCTOBER	43621	56880	58492	52998
NOVEMBER	5459	55570	59617	40215
DECEMBER	51607	67108	57655	58790

Appendix III: The Industrial Water Demand in m^3 for Two Rivers Dam catchment

	2018	2019	2020	AVERAGE
JANUARY	147	341	773	420
FEBRUARY	124	387	1261	591
MARCH	278	558	1479	772
APRIL	240	447	857	515
MAY	203	794	1161	719
JUNE	147	890	750	596
JULY	210	939	1257	802
AUGUST	165	702	2667	1178
SEPTEMBER	135	208	735	359
OCTOBER	118	334	1030	494
NOVEMBER	114	264	479	286
DECEMBER	125	367	354	282

Appendix IV: The Agricultural Water Demand in m3 for Two Rivers Dam catchment

	2018	2019	2020	AVERAGE
JANUARY	59	118	102	93
FEBRUARY	49	108	131	96
MARCH	62	84	97	81
APRIL	72	76	118	89
MAY	76	71	104	84
JUNE	53	70	75	66
JULY	71	76	111	86
AUGUST	173	68	129	123
SEPTEMBER	63	78	88	76
OCTOBER	56	130	121	102
NOVEMBER	60	126	137	108
DECEMBER	64	112	142	106

Appendix V: The Water Supply in m^3 from Two Rivers and Ellegerini Reservoirs

	2018	2019	2020	AVERAGE
JANUARY	248287	231086	255015	244796
FEBRUARY	162399	200961	250206	204522
MARCH	202426	220094	269688	230736
APRIL	193519	170048	254950	206172
MAY	250444	162795	263552	225597
JUNE	291391	213678	251370	252147
JULY	237809	237489	269069	248123
AUGUST	245296	250846	266747	254296
SEPTEMBER	233633	242354	237738	237909
OCTOBER	237495	244783	241137	241139
NOVEMBER	226268	234013	230020	230100
DECEMBER	225271	237085	232720	231692

Appendix VI: The Unaccounted-for Water (UFW) in Percentages

	2018	2019	2020	AVERAGE
JANUARY	39.45	45.9	42.33	42.56
FEBRUARY	40.77	44.31	40.74	41.94
MARCH	44.38	41.86	43.09	43.11
APRIL	34.14	37.7	42.7	38.18
MAY	44.99	38.63	45.17	42.93
JUNE	43.33	44.01	44.97	44.1
JULY	48.95	38.09	44.88	43.97
AUGUST	42.64	43.7	35.06	40.47
SEPTEMBER	40.77	43.95	39.03	41.25
OCTOBER	45.32	38.31	42.46	42.03
NOVEMBER	36.84	39.1	40.71	38.88
DECEMBER	45.57	40.43	37.36	41.12

Appendix VII: Approval of Research License from National Commission for Science, Technology and Innovation (NACOSTI)

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

Ref No: 242948

Date of Issue: 10/March/2020

RESEARCH LICENSE

This is to Certify that Mr.. Dennis Mailu Kiamba of Moi University, has been licensed to conduct research in Elgeyo-Marakwet, Kakamega, Nairobi, Nakuru, Uasin-Gishu on the topic: APPLICATION OF THE WEAP MODEL FOR THE INTEGRATED WATER RESOURCES MANAGEMENT OF THE KAPTAGAT CATCHMENT for the period ending : 10/March/2021.

License No: NACOSTI/P/20/4270 Ammended

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Director General
NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

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Appendix VIII: Approval Letter from The Eldoret Water and Sanitation Company (ELDOWAS) to Conduct Research in their Institution

ELDOWAS

ELDORET WATER AND SANITATION COMPANY LIMITED

Date 26th February, 2020

Your Ref ______

Our Ref ELDOWAS/ADM/23/IA/VOL.VI/048

Department of civil and structural Engineering,
Moi University,
P. O BOX 3900-30100,
ELDORET.

Dear Sir/ Madam,

RE: COLLECTION OF RESEARCH DATA - MR. DENNIS MAILU KIAMBA

Reference is made to your letter dated 20th February, 2020.

This is to confirm that the above named student has been granted permission to undertake a research on the Topic: **"Application of the WEAP model for the intergrated Water Resources Management of the Kaptagat Catchment."**

After successful completion of the research, the student is kindly requested to forward a copy of the findings to this Company for necessary action.

Please note that the student shall not be allowed to undertake any other activity other than the above mentioned.

Yours faithfully
ELDORET WATER AND SANITATION CO.LTD

M. BIRGEN
HUMAN RESOURCE & ADMIN. MANAGER

ISO 9001:2015 CERTIFIED

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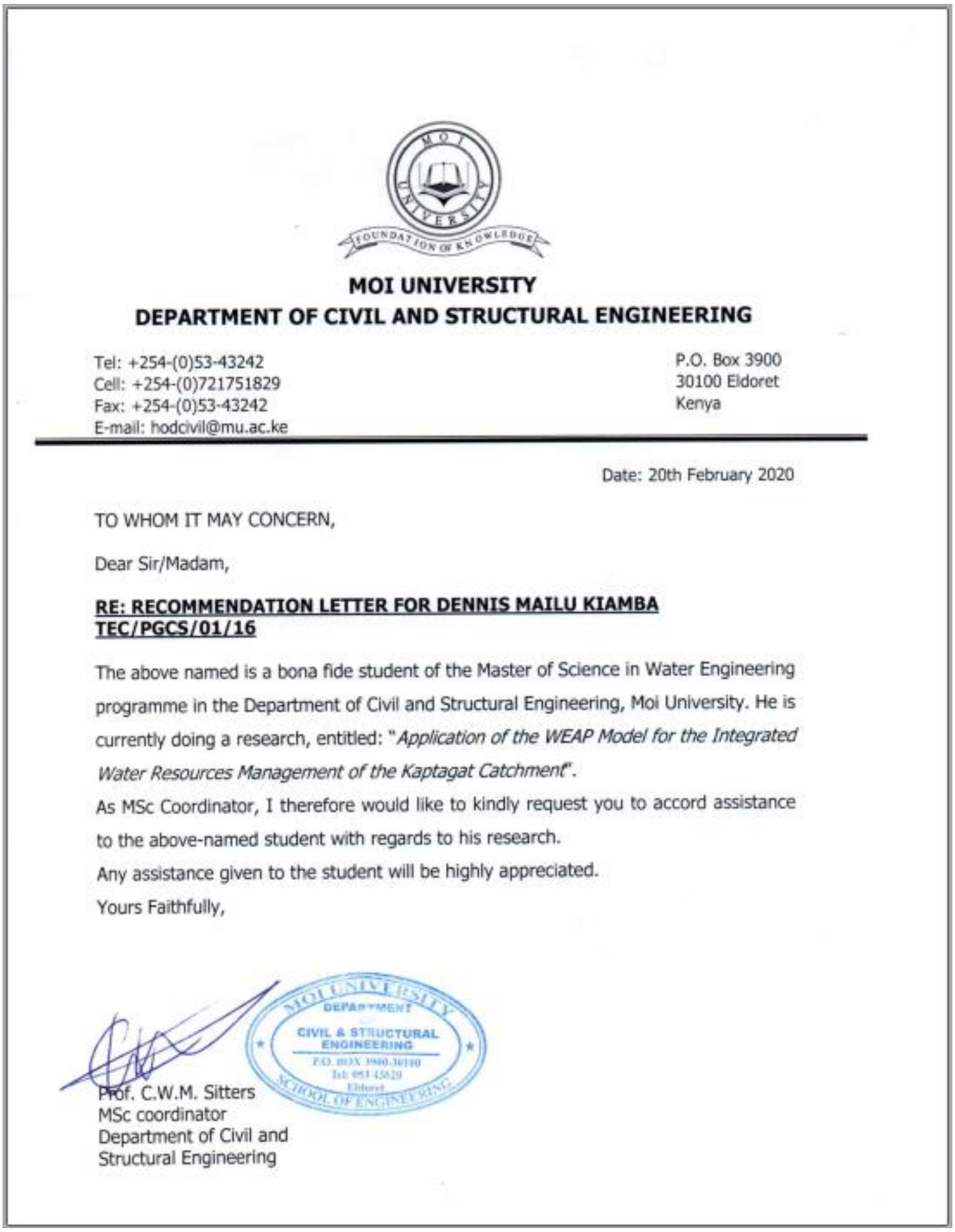
Mission: Eldowas is committed to providing quality and adequate water services in a cost effective Manner to its stakeholders by qualified and motivated human resource.

Appendix IX: Recommendation Letter from the Department of Civil and Structural Engineering of Moi University



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P.O. Box 3900
30100 Eldoret
Kenya

Date: 20th February 2020

TO WHOM IT MAY CONCERN,

Dear Sir/Madam,

RE: RECOMMENDATION LETTER FOR DENNIS MAILU KIAMBA
TEC/PGCS/01/16

The above named is a bona fide student of the Master of Science in Water Engineering programme in the Department of Civil and Structural Engineering, Moi University. He is currently doing a research, entitled: "*Application of the WEAP Model for the Integrated Water Resources Management of the Kaptagat Catchment*".

As MSc Coordinator, I therefore would like to kindly request you to accord assistance to the above-named student with regards to his research.

Any assistance given to the student will be highly appreciated.

Yours Faithfully,

Prof. C.W.M. Sitters
MSc coordinator
Department of Civil and
Structural Engineering

Appendix X: Turnitin Antiplagiarism Report

Application of SWAT and WEAP Models for Sustainable Management of Water Resources in the Two Rivers Dam Catchment, Uasin Gishu

ORIGINALITY REPORT

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PRIMARY SOURCES

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6	Jiri Nossent. "Multi-variable sensitivity and identifiability analysis for a complex environmental model in view of integrated water quantity and water quality modeling", Water Science & Technology, 01/2012 Publication	1%
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Appendix XI: Publication Associated with the MSc Thesis

Successfully Published Journal Paper in a Peer Reviewed Journal

East African Journal of Environment and Natural Resources, Volume 6, Issue 1, 2023
Article DOI: https://doi.org/10.37284/eajenr.6.1.1336

East African Journal of Environment and Natural Resources
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Print ISSN: 2707-4234 | Online ISSN: 2707-4242
Title DOI: https://doi.org/10.37284/2707-4242

EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Application of SWAT and WEAP Models for Sustainable Management of Water Resources in the Two Rivers Dam Catchment, Uasin Gishu County, Kenya

Dennis Mailu Kiamba[1], Emmanuel Chessum Kipkorir[1], Job Rotich Kosgei[1], Simon Mburu Njoroge[1] & Gilbert Nyageikaro Nyandwaro[1]*

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Date Published:

30 July 2023

Keywords:

GIS, Land Use Change, SWAT Model, WEAP Model, Calibration, Validation

ABSTRACT

Kaptagat Forest, the main source of the Ellegerini River, which feeds the Ellegerini Dam and Two Rivers Dam, is under threat of extinction due to human activity. The Two Rivers Dam catchment that has over the years been a source of water in Uasin Gishu County is slowly depleting and urgent measures are required to restore it. Activities including commercial logging, charcoal burning and firewood harvesting have exerted a lot of pressure on the catchment, posing a great threat to the livelihoods of the people of Eldoret town who depend on the reservoirs for water supply. The main objective of this study was to customise SWAT and WEAP models for the sustainable management of water resources in the Two Rivers Dam catchment. The specific objectives were to set up and apply the SWAT model to generate simulated river flows draining to the Two Rivers and Ellegerini Reservoirs as an input to the WEAP model to determine the impact of land use change on the hydrological function of the Two Rivers Dam catchment, to set up, calibrate and validate a WEAP model for the Two Rivers Dam catchment and to apply the WEAP model in analyses of various management and infrastructural development projects scenarios to enhance river flow and water storage in the Two Rivers and Ellegerini Reservoirs. The goodness of fit SWAT model statistical evaluation indices attained during the calibration period was R2 = 0.854, NSE = 0.822 and Bias = 0.392. Additionally, for the validation period, the R2 = 0.786, NSE = 0.815 and Bias = 0.381. The modelled results indicate that the land use change resulted in decreased baseflow and increased surface runoff hence the high fluctuations of water levels in the Two Rivers and Ellegerini reservoirs. The WEAP model results for actual and simulated water demand in the calibration period of 2019, the R2 = 0.88, while during the validation period in the year 2020, the R2 = 0.85. The results of the model simulation indicated that the management option that had the most impact on all the scenarios was the reduction of unaccounted-for water, while the one with the least impact was increased water use efficiency. It was concluded that

Appendix XII: Rainfall Data Calibration Period

DATE	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1	0.0	0.0	0.0	0.0	3.1	10.0	3.2	1.4	0.4	0.0	12.6	0.0
2	0.0	0.0	0.0	0.0	10.2	11.0	0.0	12.7	24.8	0.0	1.3	4.2
3	0.0	0.0	0.0	2.0	10.2	0.0	44.2	0.0	0.0	8.2	1.5	0.0
4	0.0	0.0	3.4	12.0	25.5	1.2	0.0	0.0	0.0	0.0	0.0	0.5
5	0.0	0.0	0.3	55.0	15.0	0.0	9.1	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	14.7	14.5	0.0	8.2	0.0	0.3	0.0	0.3	0.0
7	0.0	0.0	0.0	7.5	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	1.0	1.5	4.3	4.2	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	7.2	0.0	0.8	0.0	0.0	0.0	0.4	0.0
10	0.0	0.0	0.0	19.6	4.2	0.0	0.0	4.9	0.0	12.9	1.5	0.0
11	0.0	0.0	0.0	22.5	8.8	0.0	0.0	0.5	0.0	0.0	5.0	0.0
12	0.0	0.0	0.0	2.2	2.8	0.0	0.0	0.0	0.0	0.0	11.8	0.0
13	0.0	0.0	0.0	7.5	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	25.5	0.0	0.0	0.0	2.0	0.0	0.4	0.0	0.0
15	0.0	0.0	0.0	11.0	0.0	0.0	0.0	0.3	0.0	0.4	0.0	0.0
16	0.0	0.0	0.0	70.0	0.0	0.0	0.0	0.0	0.0	0.0	8.8	0.0
17	0.0	0.0	0.0	47.0	29.5	18.2	0.0	0.0	0.0	0.0	0.2	0.0
18	0.0	0.0	0.0	4.6	1.6	0.4	0.0	0.0	3.1	0.0	0.0	0.0
19	0.8	0.0	0.0	0.0	0.0	18.1	0.0	0.0	0.0	0.0	0.0	0.0
20	30.0	0.0	0.0	0.0	0.0	14.0	0.0	7.6	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	18.0	0.0	8.5	0.0	0.0	0.2	0.0
22	8.5	0.0	0.0	0.0	0.0	1.2	0.0	34.4	0.0	0.0	0.2	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0
24	3.0	0.0	0.0	0.0	0.0	12.2	0.0	0.0	0.0	0.0	0.0	0.0
25	14.7	2.3	0.0	0.0	0.0	26.0	2.2	0.0	0.0	0.0	0.0	0.0
26	5.6	35.4	0.0	0.0	17.4	8.7	3.8	0.0	0.0	0.0	0.0	0.0
27	0.0	1.9	0.0	0.0	0.0	0.0	3.1	0.0	0.0	0.0	0.0	0.0

Appendix XIII: Rainfall Data Validation Period

DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.0	14.4	32.0	13.4	1.1	9.1	1.4	4.0	4.2	1.1	0.0	3.4
2	0.0	2.2	0.0	6.8	3.3	1.8	4.7	21.0	0.0	6.3	0.0	0.0
3	0.0	8.0	0.0	3.3	0.0	15.1	0.9	0.0	3.5	0.0	0.0	0.0
4	0.0	4.3	0.0	17.7	0.8	0.0	14.8	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	15.7	14.0	8.3	0.3	0.0	0.0	5.6	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.6	12.2	0.5	0.0	0.4	15.8	0.0
7	0.0	0.0	0.0	0.0	27.3	6.9	0.2	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	46.0	0.0	1.3	0.0	0.0	29.3	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	7.9	0.0	0.0	0.0	0.0	0.0
10	3.5	0.0	0.4	0.0	0.0	0.0	6.8	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	5.2	11.9	2.7	2.2	0.0	0.0	0.7	0.0
12	0.0	0.0	4.9	0.0	3.6	0.0	0.0	0.0	0.6	0.0	16.1	0.0
13	0.0	0.0	26.8	0.0	0.7	0.0	0.0	0.0	3.3	0.0	0.0	0.0
14	0.0	0.0	24.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.9	0.0	4.9	0.0	12.0	0.0	0.0	0.0	0.4	0.0
16	0.0	1.1	5.0	0.0	1.6	0.0	15.2	0.0	0.0	0.0	0.0	0.0
17	0.0	1.0	35.0	0.0	11.9	0.0	10.6	9.0	2.9	0.0	1.4	0.0
18	0.0	0.0	0.0	18.6	0.0	0.0	1.3	0.0	1.1	0.0	9.3	4.5
19	0.0	0.0	11.5	30.0	0.0	0.0	7.8	3.2	0.0	0.0	0.0	7.5
20	0.0	0.0	13.8	33.0	0.0	0.0	3.3	0.5	2.3	0.0	0.0	3.5
21	0.0	0.0	1.3	4.7	0.0	0.0	1.0	6.0	25.7	0.8	0.0	1.5
22	0.0	0.0	0.6	13.7	0.0	0.0	0.0	0.0	12.7	0.0	0.0	3.1
23	0.0	0.0	2.5	0.4	0.0	0.0	10.6	8.5	0.0	0.0	0.0	0.0
24	0.0	0.0	9.5	3.0	0.0	0.0	3.1	14.6	0.4	0.0	0.0	0.0
25	0.0	0.0	48.3	0.0	0.0	0.0	0.0	14.2	0.0	0.6	2.6	17.1
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	14.5
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	2.9	10.6