The University of Nairobi

Faculty of Engineering

DEPARTMENT OF CIVIL AND CONSTRUCTION ENGINEERING

HYDROLOGICAL MODELLING OF IMPACT OF SMALL RESERVOIRS IN UPPER EWASO NG'IRO RIVER ON DOWNSTREAM FLOW: CASE STUDY OF NANYUKI RIVER

ABDINASIR AHMED ALI
F56/69301/2013

A Thesis submitted in partial fulfillment of the requirements for the award of degree of Master of Science in Civil Engineering (Water Resources Engineering Option) of the University of Nairobi.

November 2022

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Student Name: … ABDINASIR AHMED ALI – F56/69301/2013

Date: 14th November 2022 Signature: ………………………………………

This Thesis has been given in to for review with our approval as the appointed university supervisor(s).

Nyanchaga. 14th November 2022

……………………………………..……… ……………………………………………

Name of 1st supervisor Date

Prof Ezekiel Nyangeri Nyanchaga

………………...………………………..……… ……………………………………………

The Dean, Date

Faculty of Engineering

Declaration of Originality

Name of Student:	Abdinasir Ahmed Ali
Registration Number:	F56/69301/2013
Faculty/School/Institute:	Faculty of Engineering
Department:	Department of Civil and Construction Engineering
Course Name:	Master of Science Degree in Civil Engineering
Title of the Work:	Hydrological Modelling Of Impact Of Small In Reservoirs Upper Ewaso Ng'iro River On Downstream Flow: Case Study Of Nanyuki River

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Dedication

To My Parents.

Acknowledgement

I thank the Almighty God for His guidance through the master's education and thesis writing. Without His Support, these could not have been possible. I extend my heartfelt appreciation to my Supervisors, Prof. Ezekiel Nyangeri Nyanchaga and the Late Prof. Francis N. Gichuki - for their guidance, in-depth analysis and corrective criticisms during the period of research and thesis writing. Prof Gichuki, sadly passed away on 19th February 2021 after a short illness. Though he was not with us till the end, his contribution is manifested in this research.

Eng. Josiah W. Mulwa, HSC, of Ewaso Ng'iro North Development Authority, Eng. Diba Qalicha, Water Resources Engineer – ENNDA (Isiolo office), Mr. Peter Raburu of Rural focus, Nanyuki and Mr. Gordon Namenya of water resources authority (WRA) head office, Nairobi - for the various ways you have helped in carrying out the study especially when sourcing for the data for the research. Thank you very much.

Miss Cecilia Njeri Kagwima, thank you for your valuable time during the proofreading and corrections of the thesis.

And finally, I thank my family for their understanding and patience during the period of study.

To God be the Glory.

Abstract

The Nanyuki River originates from west of Mount Kenya and flows through the county of Laikipia, where perennial water scarcity problems lead to socioeconomic and ecological issues. Upstream of the basin, river waters are abstracted, reducing downstream flows drastically leading to disputes between rival water users. Excess river water storage (Flood storage) and management has the potential to reduce abstraction of the natural flows and prevent eminent conflicts. Nevertheless, there is very limited information on the extent and impact of storage specifically for the Ewaso Ng’iro River. The overall focus of this study was thus to identify suitable sites for dams along the Nanyuki River and evaluate the potential of flood water storage for use during dry spells to maintain/regulate downstream water flows. The specific objectives were three-fold: (i) To determine suitable dam sites and identify reservoir characteristics, (ii) To simulate downstream flows under different operational regimes using HEC-HMS model; and (iii) To evaluate the impact of the reservoirs to downstream flows using WEAP.

Documentation of possible dam sites as a strategic initiative for water resources management was evaluated using an integrated approach involving MCDA and GIS in consideration of thematic attributes. Six thematic features were considered: Stream Order, Slope, Elevation, Curve Number, Land use/Landcover and Lithology. The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) was adopted for continuous simulation of river discharge in the basin at the identified dam locations which are not gauged. Model output was harmonized with observed discharge data to establish the suitability of model in predicting streamflow. To assess the impacts of small reservoirs on maintaining the downstream flows and reduce the impact of over-abstraction especially during the dry season, the Water Evaluation and Planning (WEAP) model was adopted. Two dam locations deemed suitable were sited downstream of the catchment at location 0^{o} 12’ 35.5’’N, 37^{o} 0’ 29’’E and 0^{o} 15’ 45’’N, 36^{o} 57’0.95’’E for dam 1 and 2 respectively. Dam 1 axis elevation is 1750 meters (dam width is 460 meters and height is 12 metres), while Dam 2 axis elevation is 1694 meters (width of 600 metres and height is 14 metres). For Dams 1 and 2, the estimated water storage volumes are 5.8 and 6.1 Mm^3 respectively. Model performance was based on statistically computed parameters in addition to the visual inspection and comparison of the resultant hydrographs.

It has been noted that increasing domestic and agricultural demands were the main causes of over-abstraction - in particular - in the upstream catchments. This results to water scarcities leading to conflicts among different users in the downstream of the catchment. The study recommends flood storage in a series of small dams in the upstream to regulate and maintain dry-season flows in the downstream. Although, the benefits of water storage for the case of Ewaso Ng’iro may outweigh the negative impacts, there must be a limit beyond which such impoundment may have adverse impacts to the ecosystem functioning resulting to a shift in the balance.

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List of Abbreviations and Acronyms

AHP	Analytic Hierarchy Process
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
AVE	Area-Volume-Elevation
CHIRPS	Climate Hazards Group Infrared Precipitation with Station Data
CPA	Coefficient of Performance
CR	Crop Residue Cover
DEM	Digital Elevation Model
FAO	Food and Agricultural Organization
FDC	Flow Duration Curve
FEMA	Federal Emergency Management Agency
GIS	Geographical Information Systems
HEC-HMS	Hydrologic Engineering Centre-Hydrologic Modelling system
ICOLD	International Commission on Large Dams
ICPAC	IGAD Climate Prediction and Applications Centre
IWRM	Integrated Water Resources Management
KMD	Kenya Meteorological Department
KSS	Kenya Soil Survey
MCDA	Multi Criteria Decision Analysis
NRCS	Natural Resources Conservation Service
RCMRD	Regional Centre for Mapping of Resources for Development
RGS	River Gauging Station
SCS CN	Soil Conservation Service Curve Number
SEI	Stockholm Environment Institute
SMA	Soil Moisture Accounting
SRTM	Shuttle Radar Topography Mission
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WEAP	Water Evaluation and Planning
WRA	Water Resources Authority

1. INTRODUCTION

1.1. Background

Floods, in particular, are a significant water management tool that can actually lower the stress on river flows due to over-abstractions during dry periods. In this case, floodwaters and extra runoff are collected and stored for use during times of low flows. A popular technique of harvesting excess runoff during the peak flows is through the construction of in-stream dams. Impoundment of a river's waters to form a reservoir is done through the construction of a structure built across the river's reach that is referred to a dam. A critical step in the creation of dams is selecting suitable locations for their reservoirs. It is also crucial to establish the foundation's stability in order for it to support the weight of the materials and the impounded volume (Baban & Wan-Yusof, 2003).

Dams that are strategically placed will yield maximum benefits, including raising the area's scenic value for recreational purposes. The life and ecosystem downstream of the impoundment is, nevertheless, seriously threatened by poorly sited dams (Dai, 2016). An example would be a dam breach or break, which might result in significant damage as well as financial and human losses. Therefore, choosing appropriate sites for new dams is a procedure that must be carefully considered. Along with considering the intended dams' structural stability and integrity, dam siting also considers other crucial elements, such as the proximity and accessibility to the intended users. The selected site should also be located where the impoundment or reservoir will yield the greatest economic benefits (Ali et al., 2021).

Plate 1-1: River Likii in Nanyuki town. Notice the abstraction pipe in the background.

Land use patterns in Ewaso Ng’iro basin has steadily been transformed occasioned by high population growth mainly due to small-holder agropastoral farmers. This implies increased pressure on natural resources such as water resources especially in Ewaso Ng’iro’s upper Basin. Over time, foreign and new types of demand sectors emanating from new land uses exacerbate further the increase. Other than the need for water in the urban markets/centers and tourist resorts, increased agricultural activities also plays a key role. The river-based storage in the Nanyuki River-basin is thus insufficient to bridge the dry-season requirements with such increasing water demand from diverse sectors. Therefore, 60-95% of the available flows is abstracted in the upper basin with majority being unauthorized. Thus, little to no water is left for the downstream consumers as a result of water abstraction in the upstream regions. (Liniger, Wiesmann, et al., 2005) stated that during the driest month of the year (February), the monthly average river discharge at Archer's Post RGS, which is in the middle reaches, decreased from 9 m^3/s in the 1960s to 4.59, 1.29, and 0.99 m^3/s in the 1970s, 1980s, and 1990s, respectively. This downward trend shows that zero-flow situations do exist in important years, as they did in 1984, 1994, and the early 2000s. It is therefore necessary to store floodwaters so as to lessen social and economic impacts on the downstream especially when the water level is low in Nanyuki River.

Plate 1-2: Section of the Nanyuki River.

According to reports, the Ewaso Ng'iro catchment's downstream discharge was decreased by unsustainable water abstraction upstream, particularly during the dry months. Dams are consequently the main asset of flood storage. A study by (Gichuki, 2002) revealed that the upper Ewaso Ng'iro basin has insufficient surface water storage investments, that would have reduced conflicts between downstream and upstream water users. In this research, we aim to investigate suitable dam sites and resultant reservoir characteristics in the upper Ewaso Ng'iro Basin's Nanyuki River Catchment. Further, we examine whether building such modest reservoirs along the River reach is a sustainable strategy that can guarantee equitable distribution of available limited water resources, particularly the dry season discharges across competing demand sectors (Ali et al., 2021).

1.2. Problem Statement

The Nanyuki River flows through urban area, large scale agricultural farms and ranches undertaking both commercial farming and wildlife conservancies. There is high water demand for domestic consumption, agricultural, irrigation use and wildlife. Water from the river is not sufficient to meet all the water demand and quite often, downstream flows are drastically reduced. The reduced downstream flow of the river results to conflict between the downstream inhabitants and upstream water users including slow socio-economic growth. However, during the long rains, the river floods causing damages downstream. The study investigates the impacts of small dams on maintaining the downstream flows. Establishment of small dams to store floodwater for use in the dry seasons is thus necessary. The study seeks to establish suitable locations for small-medium water reservoirs which shall ensure runoff storage for use during dry spells to maintain/regulate downstream water flows.

1.3. Objectives

1.3.1. General Objective

The overall objective is to assess suitable sites for dams and establish desirable operational rule curve for water storage reservoir along the Nanyuki River to capture floodwater and runoff for use during dry spells to maintain/regulate downstream water flows.

1.3.2. Specific Objectives

1. To determine reservoir characteristics and select suitable dam sites.
2. To simulate downstream flows under different operational regimes using Hydrologic Engineering Centre-Hydrologic Modelling system (HEC-HMS).
3. To evaluate the impact of the reservoirs to downstream flows using Water Evaluation and Planning (WEAP) tool.

1.4. Research questions

1. Can suitable dam sites be accurately selected with the application of remote sensing and GIS and a corroboration with limited ground truthing?
2. How can reservoir characteristics – Area-Volume-Depth – relationships be accurately determined from global elevation data to support predication of water availability and allocation in water scarce catchments?
3. What are the possible impacts of flood alteration using small dams on the dry-season hydrological regime and equitable allocations in water scarce catchments?

4. Can small on-stream dams with a properly designed operational rule solve the puzzle of dry season flows in a typical highland-lowland system?

1.5. Justification for the Study

The Nanyuki River flows through Nanyuki Town, the county seat of Laikipia County, and is and forms part of the upper Ewaso Ng'iro Basin. The river flows from the lee part of Mount Kenya and provides water both for domestic and agricultural uses as it meanders through the plains. The water demand in the basin has been on the rise due to high population growth occasioned by immigration that has resulted to diverse change in land-use practices mainly from natural flora to small-scale commercial farming. Without any reasonable surface water storage infrastructure, there is definitely increased pressure on the available water resources.

The source of all the forms of upstream/downstream conflict among the inhabitants in the research basin has an inclination on the hydrological phenomenon where in the recent past annual rainfall has drastically reduced and thus leading to decreased downstream flow. Flood storage and management has the potential to reduce abstraction of the natural flows and prevent eminent conflicts. Such potential if exploited can reduce dry season flow abstractions and ensure that sufficient water is obtainable for downstream water users. However, there is very limited information on the extent and impact of storage specifically for the Ewaso Ng’iro River. Reservoirs or dams are constructed to harvest excess river water during wet seasons for future use as well as a measures to help flooding rivers (Gichuki, 2006). They are also used to regulate water flow and reduce upstream abstraction from the river.

This research seeks to demonstrate flood storage and management using small dams can substantially increase dry seasons’ flow and decrease abstraction which is a major source of conflicts between downstream and upstream users. During the dry seasons, dams would lower water pressure and direct stream flow abstraction in the upstream and thus allowing substantial flow of discharges to the downstream of the catchment. Further, dams would act as buffers preventing the movement of pastoralist to the upstream of the catchment to conflict with the farmers. The research entails selection of suitable dam sites, rainfall runoff modelling using HEC-HMS to obtain discharges at ungauged suitable dam locations and use of Water Evaluation and Planning model (WEAP) which vital tool for water allocation. We therefore demonstrate that the application of multi-method approach that includes the application of Remote sensing and GIS in assessing critical water issues. Geographic Information Systems (GIS) and remote sensing are key technologies that enable ease of access, handling, manipulation of data critical for decision making (Ali et al., 2021).

2. LITERATURE REVIEW

2.1. Water Situation in the Global Context

Global demand for water to support socio-economic development which is on the steady rise due to the growing world population is expected to escalate water scarcity (Khan et al., 2018; Mekonnen & Hoekstra, 2016; Pedro-Monzonís et al., 2015). The big question in the current century is whether the limited freshwater resources will ever be sufficient to meet the ever growing demand resulting from the increasing population (Kummu et al., 2016). There is no doubt that, unsustainable exploitation of the dependable water resources is already threatening the sustainability of available freshwater resources (Almer et al., 2017; Mutambara et al., 2016; Wong & Pecora, 2015). Previous studies on environment and in particular freshwater ecosystems, food and industrial development have highlighted that more developing countries are bound to have a persistent water scarcity. Already, countries in Sub-Saharan Africa are confronted with intermittency of freshwater resources resulting to conflicts on the extreme (Conway et al., 2009; Ringler et al., 2010; Schuol et al., 2008; Van Koppen, 2003). Therefore, the need to establish workable mechanisms to effectively manage the limited water resources in a manner that ensures equitable allocation while maintaining ecosystem integrity has been on the rise (Khan et al., 2018). Properly designed water allocation management plans and agreements are fundamental in resolving conflicts over access to water (Rahmati et al., 2019).

Although goals and methods have changed over time, the process of making critical decisions across competing demands has remained fundamentally unchanged (Hoekstra et al., 2016; Petts, 1996). Over the ages, difficulties have forced changes in water distribution plans, including an increase in water abstraction (Liniger, Wiesmann, et al., 2005; Van Koppen, 2003; Wong & Pecora, 2015); closure of a basin and the absence of further locations for water infrastructure; expansion and economic change, which result in a greater range of water users with various water needs; climatic change, the loss of river functions, and the deterioration of freshwater ecosystems (Wada et al., 2014). In negotiations with water allocation, it has turned into a balancing act with complicated rules. Approaches to allocating water are frequently based on intricate criteria for coping with uncertainty while taking into account the environmental, political, and socio-economic repercussions of various scenarios of allocating water (Aeschbacher et al., 2005; Liniger, Gikonyo, et al., 2005; Liniger, Wiesmann, et al., 2005).

2.2. The Highland-Lowland System of Upper Ewaso Ng'iro

Equitable water allocation is even more complex for the case of highland-lowland systems due their fundamental function of transfer of natural resources from highland to lowlands considering the increasing pressure on natural resources. Steep vertical gradient that are both zonal and azonal conditions and physical processes that are dominantly gravity controlled are the main features of the highland-lowland system (Liniger, Wiesmann, et al., 2005). The highland-lowland systems have indicated high sensitivity to anthropogenic activities which tends to interfere with the hydrological processes. Therefore, land use practices in such complex ecosystems should be adapted to the ecological features in a manner that ensures sustainable utilization of natural resources without augmenting the existing vertical processes. The Upper Ewaso Ng'iro Basin for which the Nanyuki River Catchment forms part is a typical highland-lowland system with the features including the complexity of the involved dynamics are by far illustrative of and comparable to many regions of the world (Kiteme & Gikonyo, 2002; Liniger, Gikonyo, et al., 2005; Liniger, Wiesmann, et al., 2005). As such, Mt. Kenya serves as key water tower ensuring constant water supply to the arid (semi) lowlands. However, equitable allocation of water resources remains the main challenge and has over time resulted to frequent conflicts between competing water users along the river (Aeschbacher et al., 2005). Although, water resources users' association have been established across the watershed to play a vital water allocation plan, they are not yet to significantly impact the present water resource developments in the watershed. Plate 2.1 showing dry river bed in Merti, lowland of Ewaso Ng'iro river.

Plate 2-1: Ewaso Ng'iro river in Merti.

2.3. Water Storage in a Highland-Lowland System

Floods are a fundamentally viable water management tool that have the ability to lower dry season over-abstractions by reducing demand on river flows. In this instance, floodwaters and extra runoff are collected and stored for use during times of low flow season (Ali et al., 2021). In addition to reducing dry season abstractions, flood water storage also ensures constant water availability all year round and thus reducing periodic conflicts particular between farmers in the upstream and other downstream users such as the pastoralists. Previous studies on flood storage in a highland-lowland system have focused on the off stream water storage infrastructures such as large communal dams and farm ponds. Cortes et al., (1998); Mantel et al., (2010); and Nyssen et al., (2011) suggests that the conventional infrastructure such as dams, barrages among others retain flows during the dry periods and thus reducing further the downstream flows. Can small on-stream dams with a properly designed operational rule solve the puzzle of dry season flows in a typical highland-lowland system (Figure 2-1)?

Several studies have indicated that dams and impoundments along river reaches impact negatively on the downstream hydrology including the natural ecosystem. Some of the documented impacts of dams on the river ecological functioning include: induced sediment transport and sedimentation of the river channel/erosion balance, modification of flow velocities' distribution and induced river channel incision, modified instream biogeochemical loops and water exchange that ultimately affects overall water quality among others (Lessard & Hayes, 2003). Further, dam operation introduces negative impacts on macro-invertebrate communities through river base flow alteration. However, other studies have noted that storage reservoirs may ensure increased downstream discharges during the dry periods (Figure 2-1 Adapted from FAO, Register of African Dams and Reservoirs).

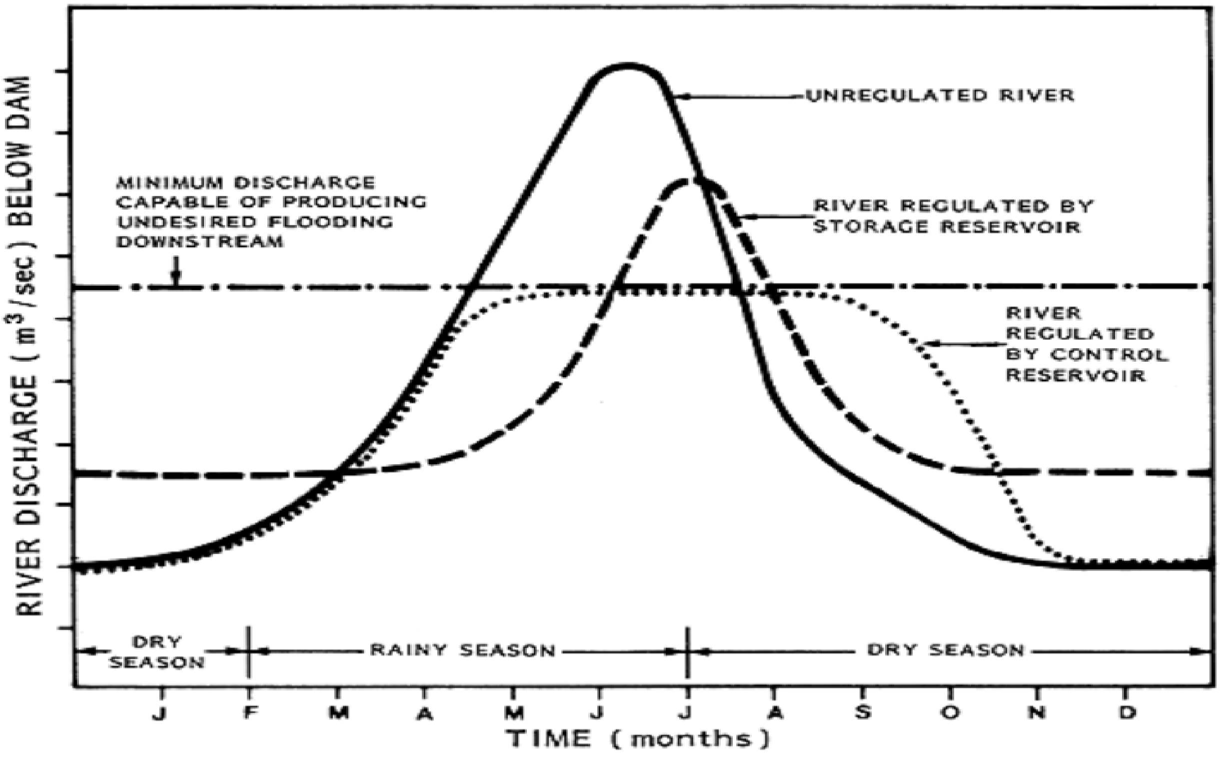


Figure 2-1: Hypothetical annual discharge for a typical African river.

The impacts of dams on the downstream ecosystem are dependent on the size and the intended purpose of the dam. Dams as water storage infrastructures can be classified in various ways depending on the function, design and structure. Of critical importance to this study the functional classification in which dams are constructed for storage, diversion, or detention (Kutzner & Kutzner, 2018). Storage dams capture and store water in the wet seasons for later usage particularly during the dry periods. Such dams provide water to augment water supply or maintain the ecosystem including the fish and wildlife habitat. Diversion dams are mainly built for irrigation purposes since they are designed to provide sufficient pressure to allow flow of water in the conveyance systems (Magilligan & Nislow, 2005). Floods are controlled by detention dams which retard flow to the downstream of the river. Storage and/or detention dams whose main purpose is augmenting supply for water consuming uses may have adverse downstream impacts to the downstream ecosystem if not properly designed (Rosa et al., 2004). See below Plate 2.2 River Timau in Nanyuki, with human interventions shown.

Plate 2-2: Timau river in Nanyuki. Human interventions near the river.

2.4. Dam Siting

Dam site selection is a crucial step in reservoir construction because it affects a wide range of variables, including both anthropogenic or human-related societal and environmental aspects. (Noori et al., 2019). For dam siting and design, a variety of factors are taken into account, including topography, soil qualities, slope, land use, current development, and seismicity of the dam site (Şel and Al-Seba'I, 2002).

An important considerations for reservoirs construction is topography (Ali et al., 2021). It significantly affects how flows are routed through upstream catchments, leaving the landscape or soil seeming bare. Its description incorporates the ground terrain, hydrological boundaries, and surface characteristics including slope and terrain features (Ajayi et al., 2018). The site must be well drained and gently sloping, preferable since it lowers building costs. Gradient has an effect on dam protection because steep slopes pose a higher risk for occurrence of landslides exerting more strain on the foundations. The type of reservoir is guided by the geological base on site. Accomplished rock base foundations are seen to have moderate to high resistance to erosion, percolation and heaviness (Mukiri & Mundia, 2016). Land use, land cover changes strongly influence the hydrological cycle due to plant type morphology and plant cover density (Yasser et al., 2013). A suitable reservoir location should have a flow contributing area that is neither too small to prevent the reservoir from overflowing, nor too large to necessitate the construction of a costly spillway. The reservoir location ought to be effectively open so that the appropriate population can be economically connected to it (Şel and Al-Seba'I, 2002). Is the highland-lowland system different from other systems when it comes to using traditional methods to site a dam that primarily seeks to preserve dry season flows?

Increasingly nowadays, environmental and socio-economic factors are also considered as key factors when siting dam such as proximity to demand site while ensuring safety of the population and sustainability of the historically beneficial sites. Table 2-1 illustrates criteria adopted as constraints for reservoir siting.

Table 2-1: Reservoir Location Constraints

Criteria	Consideration
Proximity to settlement, grazing lands	Safety and conflict prevention
Be on water accumulated zones (rivers)	Water availability
Be on a gently slope	Environmental and safety
Be on an area with less infiltration	Prevention of excessive losses from storage through seepage
Be on low elevations	Exclude highly populated highlands

Source: (Gupta et al., 1997)

Dam site selection is typically a difficult problem that is generally carried out outdoors in the field using conventional methods (Noori et al., 2021). The procedure is typically carried out utilizing traditional methods, such as traditional decision-making methods that occasionally skew toward political objectives (Al-Ruzouq et al., 2019). Use of aerial images, maps and remote sensing data which give information on the terrain and hydrological conditions before the actual field work activities inform proper dam sitting. For large sites and watersheds, such data points out unfeasible locations thereby saving time. Particularly important tools for decision makers are GIS and RS because they make it simple to access, generate, handle, and manipulate data. The use of many criteria in GIS enables the determination of priorities for effective data collecting and usage. The tools have a high degree of adaptability when combining spatial data with several existing strategic approaches to decision making that include weighted overlay analysis, multi-criteria evaluation, , artificial intelligence process, among others (Arabani & Nashaei, 2006; Jozaghi et al., 2018; Noori et al., 2019).

GIS and MCDA are two of these techniques that are frequently employed. Decision analysis often entails methodical techniques used to evaluate difficult decision problems with reference to siting. While MCDA contrasts options, GIS provides avenues for decision making spatially. MCDA relies on particular distinctive choices and adopts a given, constrained set of qualities (Al-Ruzouq et al., 2019; Rahmati et al., 2019). As a result, the strategy calls for clear, objective information on the decisions in question, with an emphasis on the important results (Ali et al., 2021). Understanding the relative importance of the many layers and attributes, as well as how each one affects the evaluation of the alternatives, was necessary for MCDA (Chezgi et al., 2016).

The selection of appropriate sites utilizing GIS, RS, and the MCDA technique has been the subject of numerous research (Ahmadullah & Dongshik, 2015; Buraihi & Shariff, 2015; Jozaghi et al., 2018; Rahmati et al., 2019; Saha et al., 2018). In the Greater Zan Region of Northern Iraq, suitable dam locations were identified through the Analytic Hierarchy Process (AHP) and fuzzy logic where spatial attributes of hydrometeorological characteristics, land cover, lineaments (fault lines), geology, soil and lithology (Noori et al., 2019). When building underground dams in Iran's Alborz Province, the spatial multi-criteria evaluation was conducted, (Chezgi et al., 2016) noted that the method displayed practical results and presented opportunities for scaling the approach to other places. Through GIS and machine learning, possible dam sites were mapped in Sharjah and United Arab Emirates demonstrating that the same approach may be used to find potential dam sites elsewhere (Al-Ruzouq et al., 2019). Based on the reservoir's size and planned use, all of these studies have utilized a variety of methodologies and characteristics. (Saleh Alatawi, 2015) utilized a four-criteria method to find the best location for a dam in Northwest Saudi Arabia, taking into account the catchment lithology, soil type, land cover and slope. As opposed to (Yasser et al., 2013) who used a combination of 18 criteria to assess the suitability of potential dam sites. The criteria included; budget, yield, impacts on health, topography, access to site, economic impacts, water quality, discharge regime, reservoir storage volume, sediment yield and load, intended water resources transfers, dam break likelihood, evaporative losses, expected maximum flood, and political and socio-environmental impacts.

Generally speaking, determining the optimal criteria for choosing dam sites is a challenging and intimidating undertaking that necessitates having a comprehensive grasp of the desired goals for the proposed dams/reservoirs (Al-Ruzouq et al., 2019; Chezgi et al., 2016; Saha et al., 2018) Of importance, are factors such as hydrological conditions, slope and the eventual safety of dam infrastructure. This study focusses on dams primarily intended to maintain dry season flow, attention was therefore given to important biophysical factors, such as elevation, slope derivatives and stream density, soils, land use and land cover and the Soil Conservation Service Curve Number layer (Ali et al., 2021).

2.5. Reservoir Characteristics

The qualities of the planned dam must be evaluated when a suitable location for its construction has been found, and this evaluation often depends on the dam's height (Sayl et al., 2017). Construction of dams, especially in the Highland Lowland arrangement such as the Ewaso Ng'iro, that has the ability to store large water volumes to support flows throughout the dry season. On the other hand, the planning and administration of the development process are frequently inadequate. Water resource managers can guarantee satisfaction of all demand sectors by calculating the amount of storage volume that is available for such reservoirs in advance (Adham et al., 2018). The ideal dam height, which will guarantee the preservation of optimum reservoir qualities, is a crucial dam feature.

Shallow broad reservoirs naturally experience larger evaporation losses than deep narrow reservoirs due to the geometry of the reservoir. (Al-Ruzouq et al., 2019; Sayl et al., 2017) established that the volume-surface area of the reservoir are directly affected by the depth of the dam. The Area-Volume-Elevation (AVE) curve, a key storage volume property, is typically a crucial aspect of dam features (Figure 2-2). To ensure sustainable water abstraction rates and to monitor reservoir sedimentation rates, it is important to acquire this relationship (Napoli et al., 2014). It's crucial to note that a reservoir's water balance, or the inflows and outflows from the reservoir, determines the amount of water that can be captured by the reservoir and is generally referred to as storage capacity. (Ali et al., 2021; Sayl et al., 2017) explains that because it is crucial for determining the best surface area, best depth, and highest capacity for reservoirs used for flood storage, the AVE curve is critical for water resources planning, management and modeling.

Estimating reservoir storage volumes can be done through adopting indirect and direct approaches – use of topographical maps and dams survey respectively (Ahmed et al., 2016). Field research is typically time- and labor-intensive, necessitating greater human and financial resources. Proper approaches to water resource planning are now more important than ever, especially for highland-lowland systems that present numerous problems with water allocation. For instance, it is critical to accurately estimate reservoir parameters with the least amount of financial impact. GIS offers the chance to accurately evaluate reservoir parameters, which improves decision-making in terms of effectiveness and dependability (İrvem, 2011). Due to its capabilities for interpreting and transforming spatial data, GIS is essential for assisting in making critical decisions. The mass balance approach, is a method frequently used to ascertain a reservoir's storage characteristics. GIS has been used in numerous studies to calculate and evaluate the potential of infrastructure for harvesting rainwater(Adham et al., 2018; Gupta et al., 1997; Mahmoud et al., 2015; Napoli et al., 2014; Sayl et al., 2017). (Jasrotia et al., 2009) noted that GIS-based method takes less time and generates AVE curves with relative errors that are precisely below 20%. In this study, we used

GIS to modify a Digital Elevation Model (DEM) with a 30 m resolution in order to assess and extract the AVE parameters for the two chosen dams. When combined with GIS, geospatial data (DEM) has proven to be a potent and affordable tool for calculating reservoir parameters vital to dam development and operational management (Ali et al., 2021).

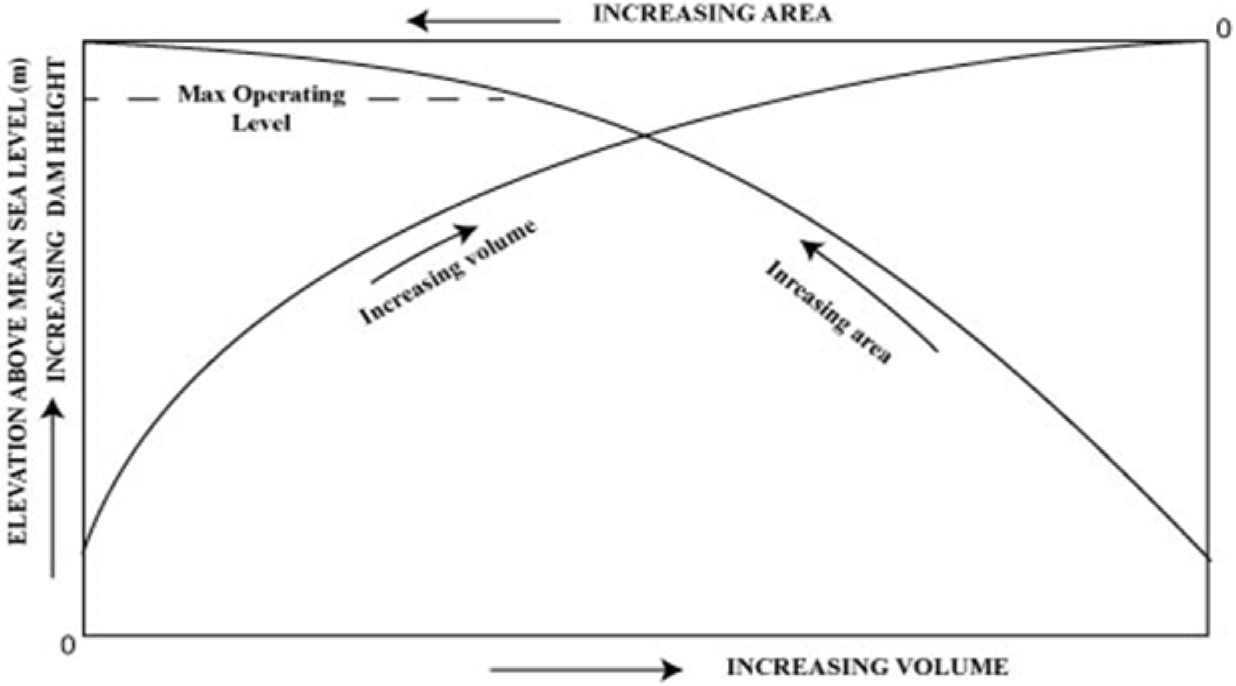


Figure 2-2: Curve typical of the reservoir Area-Volume-Elevation relationship.

2.6. Rainfall-Runoff Modelling Using HMS

Catchment hydrology depends on the climatic, land cover and use, soil and topographic conditions of the catchment. Hydrological modeling helps us understand the processes of transforming rainfall into runoff at a given set of topographic, soil, land use and cover conditions. The HEC-HMS - is a model designed for modelling continuous as well as event-based hydrologic occurrences and was conceived by United States Army Corps of Engineers (USACE) Hydrologic Engineering Center in the year 1998 (Abushandi & Merkel, 2013; Halwatura & Najim, 2013). It is an integrated modelling software that helps simulate hydrologic processes mainly on dendritic catchments. The model consists of: Basin, Meteorological, Control specification and Input data components. For the input data component consists of time series, paired data and gridded data (Chu & Steinman, 2009; Feldman, 2000; Roy et al., 2013). For the model output to be credible, HEC-HMS need to be calibrated, validated to assess its performance and sensitivity analysis is needed to assess which parameters require high level of data accuracy. One part of data is used for calibration, afterwards the other part of the data is used to authenticate the model. Once calibration and authentication has been done, then a sensitivity analysis is carried out. Sensitivity analysis is important in that it helps one understand the level of impact each parameter used in the model has on the results, thereby identifying the most sensitive parameters. The studies indicate that the model based simulation output depends on site and different model combination set-ups respond variably (Bhuiyan et al., 2017; Feldman, 2000; Roy et al., 2013).

Other researchers have used the model for simulation of run-off in arid (semi) catchments and established that the model predictions of discharges were fairly good (Akter & Ahmed, 2015; Choudhari et al., 2014; Jin et al., 2015; Yener et al., 2007; Yusop et al., 2007). (Azmat et al., 2018; Benavidez et al., 2016; Meenu et al., 2013) investigated climate change impacts on catchment hydrology using HEC-HMS, he stated that the forecasts from the model were generally accurate. They however highlight carrying out such study by coupling a single hydrological model underestimates the high flows. Kaboosi & Jelini, (2017) adopted HEC-HMS to analyze the impacts on flood control of detention reservoirs and highlighted that the efficiency of reservoirs on modifying the flood discharge and volume downstream of the storage dam. HEC-HMS has been applied on limited studies to investigate the potential of small reservoirs in maintaining dry-season flows in a typical highland-lowland system. Storage reservoirs are known to decrease maximum peak flows whose effect decreases with increase in flow duration and increases minimum low flows (Magilligan & Nislow, 2001).

2.7. Water Resource Planning Using WEAP

WEAP is a computer model used as a tool in Integrated Water Resources Management (IWRM) designed to simulate analysis of trade-offs in water supply systems within a river system. The system is based on accounting for the use of water over a defined timeline, this timeline being a month most often. Simulation enables projection and assessment of policies that include conservation of water programs, changes in the hydrologic systems, prediction of water demand, changes in water use and prioritizing allocation and development of new infrastructure. The simulation also enables assessment of different 'what if' scenarios. The model was conceived by the Stockholm Environment Institute (SEI) in Boston. The Model characterizes water resources system with respect to the supply sources (such as streams, rivers, reservoirs, watershed exchanges, and groundwater); abstraction, distribution and facilities for treatment of wastewater; ecosystem needs, water use demands (such as, domestic uses, power generation, irrigation, etc.) (Gao et al., 2017). The model uses a river system, along which it performs mass balance between the inflow and withdrawals. The model is configured to simulate a recent year (referred to as the baseline year), during which the water supply and the demand has been determined. Once this is done, then the model can be applied to simulate other different scenarios, i.e., make predictions based on what if scenarios, to evaluate impacts due to various development and management alternatives. In conclusion, WEAP is considered an IWRM tool for balancing water supply and demand by evaluating the water use and allocation (Li et al., 2015).

3. MATERIALS AND METHODS

3.1. Study Area Description

The Nanyuki river Catchment is situated between central Kenya, in the upper portion of the Ewaso Ng’iro North Catchment (shown in Figure 3-1). Of Kenya's six water catchment regions, the Ewaso Ng'iro Catchment Basin is the largest (Mutiga et al., 2010). Since the Nanyuki river originates from Mount Kenya, it receives a lot of rainfall, creating numerous perennial streams. In the upstream reaches of the Ewaso Ng'iro River, which the Nanyuki river empties into, there have been various water abstractions for domestic and agricultural usage. Due to this, the river's water flow has been dramatically reduced to worrisome levels. Because of the wide disparity in elevation, the Nanyuki River Basin often experiences a range of weather extremes, from arid (semi) to humid (Ali et al., 2021).

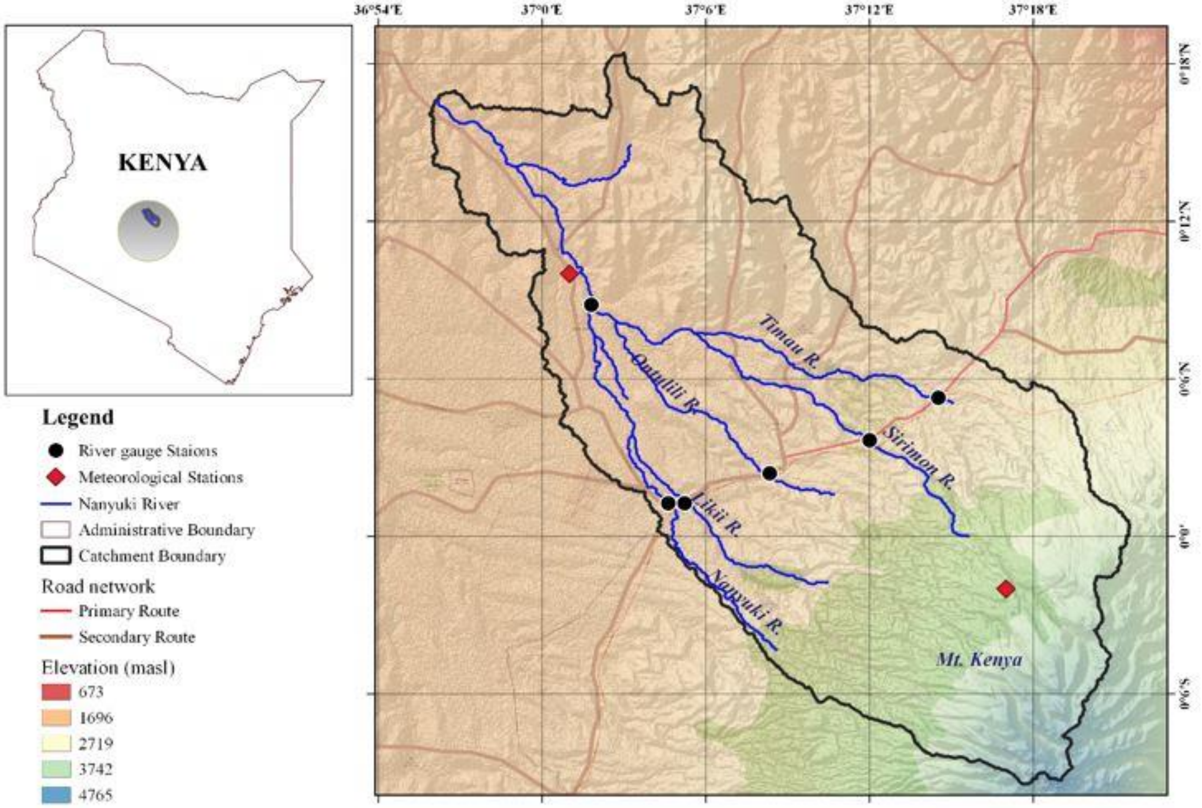


Figure 3-1: Drainage basin of the Nanyuki River.

The annual precipitation patterns show significant spatial and temporal differences, with 300 mm in the watershed's southern parts and 1500 mm in the Mt. Kenya region (Aeschbacher et al., 2005; Liniger, Gikonyo, et al., 2005). The short rainy season starts in October and lasts until November, whereas the long rainy season starts in March and lasts until May. Mean temperature ranges between 16^o C and 26^o C annually for the Laikipia county.

Plate 3.1 shows water harvesting on dry river bed in Merti.

Plate 3-1: Water harvesting on dry river bed in Merti.

3.1.1. Physiographic features, Land Use and Soils

The topography in the Nanyuki watershed is majorly dominated by Mt. Kenya (Fig. 3-1). Altitude varies from 862 m above mean sea level (amsl) to approximately 4765 m at the top of Mt. Kenya. The slopes of the mountain consist of V-shaped valleys that are deeply incised where elevation ranges between 2,500 m and 4,000 masl. The supple plateau's undulations in the downstream of the catchment has elevation varying from 1,500 m and 673 masl. The Nanyuki River watershed contains part of the forest surrounding Mt. Kenya. The forest known to be preservation of a complex collection of flora and fauna, is threatened by an alarming rate of logging (Ericksen et al., 2012; Georgiadis, 2011; Ngigi et al., 2008). The watershed has large coffee farms that encroach the forest on the slopes of the mountain and a mix of large and small scale cultivated farm land that stretch further downstream of the basin. Downstream of the basin is characterized by arid (semi) conditions with shrubs and bushlands as the main vegetation cover. The soils in the Nanyuki catchment are categorised on the basis of the terrain under which they are formed. Soils possess a high level of fertility which can support productive agricultural practices (Haruna et al., 2014). In this case therefore, limiting factors to agricultural productivity are the unpredictable weather patterns characterized by frequent dry and patchy distribution of precipitation in both space and time. The basin landscape is made up of the red volcanic soils, black cotton soil, sandy loam soils, clay loam and sandy soils (Speck, 1982). Clay is the most common type of soil in the study region. The middle portions of the basin have loam soils.

3.2. Methodology

3.2.1. Dam Siting

This study used an AHP MCDA along with GIS to determine and identify the best locations along the river to site dams (Iftikhar et al., 2016). A four step approach was used in the implementation: 1) data gathering and capture in accordance with the various site selection criteria, 2) data processing to create thematic layers, 3) To create a dam suitability map, thematic layers were defined and constraints as well weighting factors assigned based on the level control on dam site choice for each individual layer 4) and verification, as well as appropriate site selection. The suitability map, which is the main output of the procedure, was produced by combining ordered theme layers with a weighted overlay analysis. Figure 3-2 illustrates the procedure used in creating a site suitability map that was used to select appropriate sites for the two dams. Data collection, the creation of thematic layers, modeling and mapping, and validation and site selection are the four phases of the approach. (Ali et al., 2021).

Step 1 – Data Acquisition: Three different categories of information were gathered from various sources of raw data gathered to create thematic layers. The following data sets were gathered for this purpose:

- **Digital Elevation Model (DEM)**: A 30 m resolution imagery from Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) DEM was used and processed through Geographical Information System software and techniques producing the catchment boundary and stream networks (Kim et al., 2020). The USGS Earth Explorer website is where the DEM was downloaded from (https://earthexplorer.usgs.gov/). From the DEM, elevation, slope, and stream density are produced.
- **Land-use**: Land use, land cover data was obtained from the Regional Center for Mapping of Resources for Development (RCMRD) geoportal. Ten different land cover classes were established based on the classification of land cover using Sentinel 2 photos from 2016. Later, the ten classes were reclassified into four main land-use categories by grouping classes that shared comparable traits. In order to produce the SCS Curve Number, soil and landcover are integrated.
- **Soil data**: The IGAD Climate Prediction and Applications Centre Geoportal was used to gather soil data (http://geoportal.icpac.net/layers/geonode%3Asoils). The soil's physical and chemical characteristics are depicted in the covering. Kenya Soil Survey (KSS) first prepared the soil in 1982, and it was later amended in 1997. Based on the provided textural description, hydrologic soil groups were translated from soil data which was coupled with land cover data to produce the Curve Number that aided in separation of rainfall excess.

Step 2 – Preparation of thematic layers: Thematic layers were generated from processing the obtained raw data. For the research field, six thematic layers were created. Elevation, slope, stream order, geology, soil and land use are the key factors used in the selection of suitable dam sites. The 30 m DEM was used to extract hydrological attributes such as flow accumulation, stream network and density, altitude and slope. From the three sets of acquired data sets, six thematic layers were extracted (Figure 3-3).

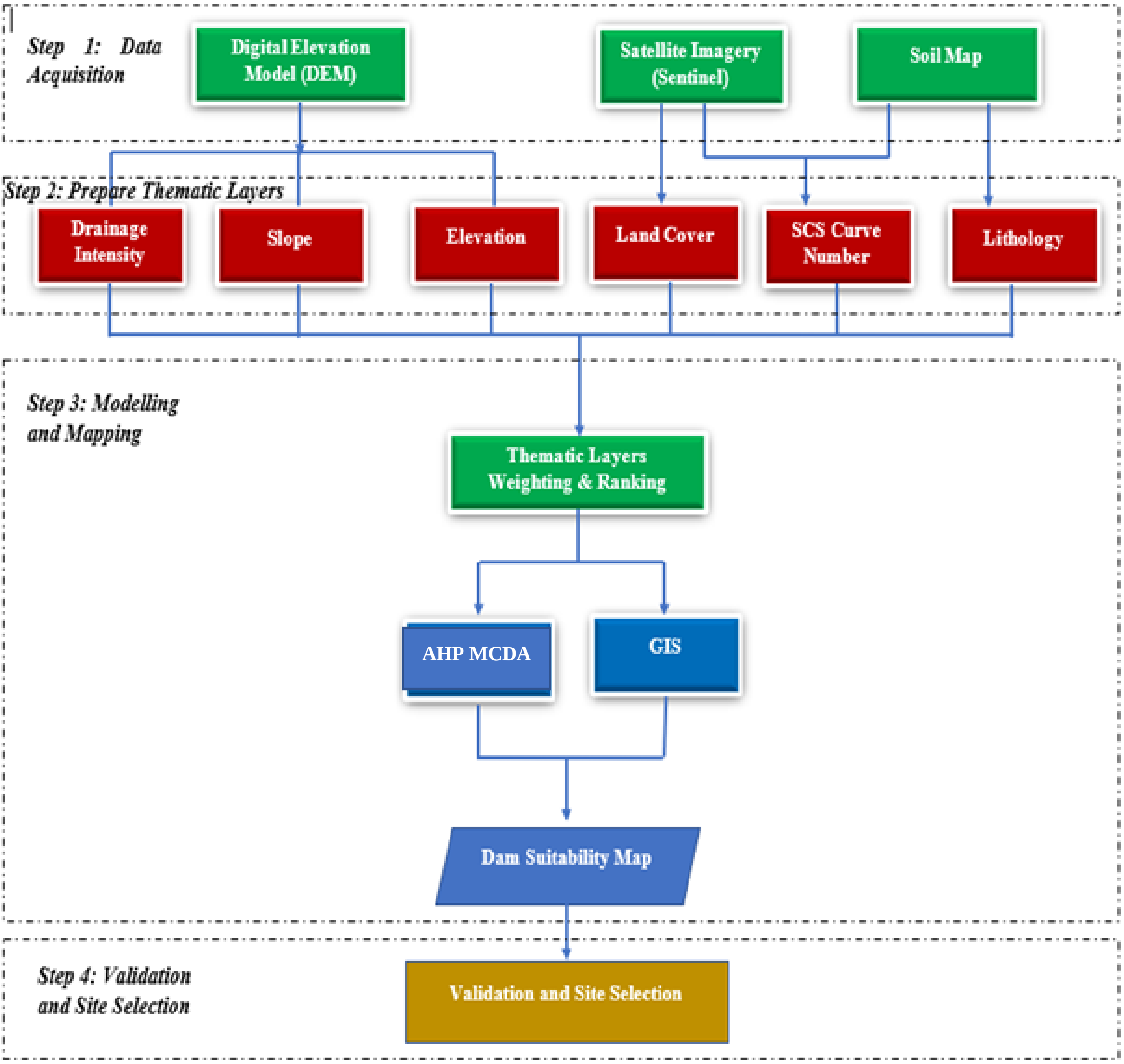


Figure 3-2: A methodical approach to choosing appropriate locations for the dams.

An elevation raster was created with heights ranging from 1678 m to 4898 m above sea level using the acquired DEM. The manner in which water flows and gathers is influenced by the DEM. Low elevation sites are perceived to be favorable for dam siting due to the potential of collecting substantial volumes. Low elevation also offers wider areas where enough run-off quantities can be accumulated. A site that is suitable for building a dam should be well drained and slightly sloping. Generally, water velocity is affected by slope parameters since lower slopes provide water accumulation a chance to happen. Slope also has an impact on the safety of dams since steep slopes put more pressure on the foundations and are more susceptible to landslides. From the obtained 30 m resolution DEM, slope was derived similarly to elevation.

On the other hand, land cover made up of vegetation prevents wind and water-related soil erosion, resulting in reduced erosive activities. Wooded Grassland has the best rating in this area. Data derived from satellites was used to create the landcover layer. The selected site should have little seepage losses, a feature of clay soils thus, clayey soil was assigned the highest scale. The Curve Number (CN) additionally offers a proxy way of defining the scope of infiltration/seepage losses while also forecasting direct runoff retention. The soil type, land use/cover, and hydrogeological state of the research area all have an impact on the CN. Low CN indicates equally low suitability for reservoir siting. Suitable dam locations are typically found along high order streams in the low elevations and are characterized by bigger catchment areas. Dams are only sited along water courses when the stream factor is taken into account during the suitability assessment process.

Step 3 – Modelling and Mapping: The most suitable locations were modelled and mapped by processing the thematic layers. Table 3-1 shows the relative weights of the various thematic levels. The study employed the following criteria to choose appropriate dam locations in accordance with FAO recommendations: to avoid densely populated area, land us land cover was used, while defining infiltration and seepage losses, the soil texture parameter was considered. Curve number represents runoff retention properties while stream order represents hydrology. It was decided to assign weights based on the relative importance of the chosen layers using a scale of 1 to 5.

A square framework was also used to give weightage to the parameters by assigning the diagonal element a value of 1. The weightage was then determined using the eigenvalue and corresponding eigenvector of the AHP correlation grid. Based on the constraints set in Table 3-1, weights were assigned to each parameter. The Hierarchical Process was used as a tool for MCDA and provided direction for choosing which layers to prioritize.

Step 4- Validation and Site Selection: To achieve the desired accuracy, the results were tested and weighting was adjusted. Drainage streamlines in vector format were overlaid to facilitate location of optimum sites for capture of runoff for later release during the dry season.

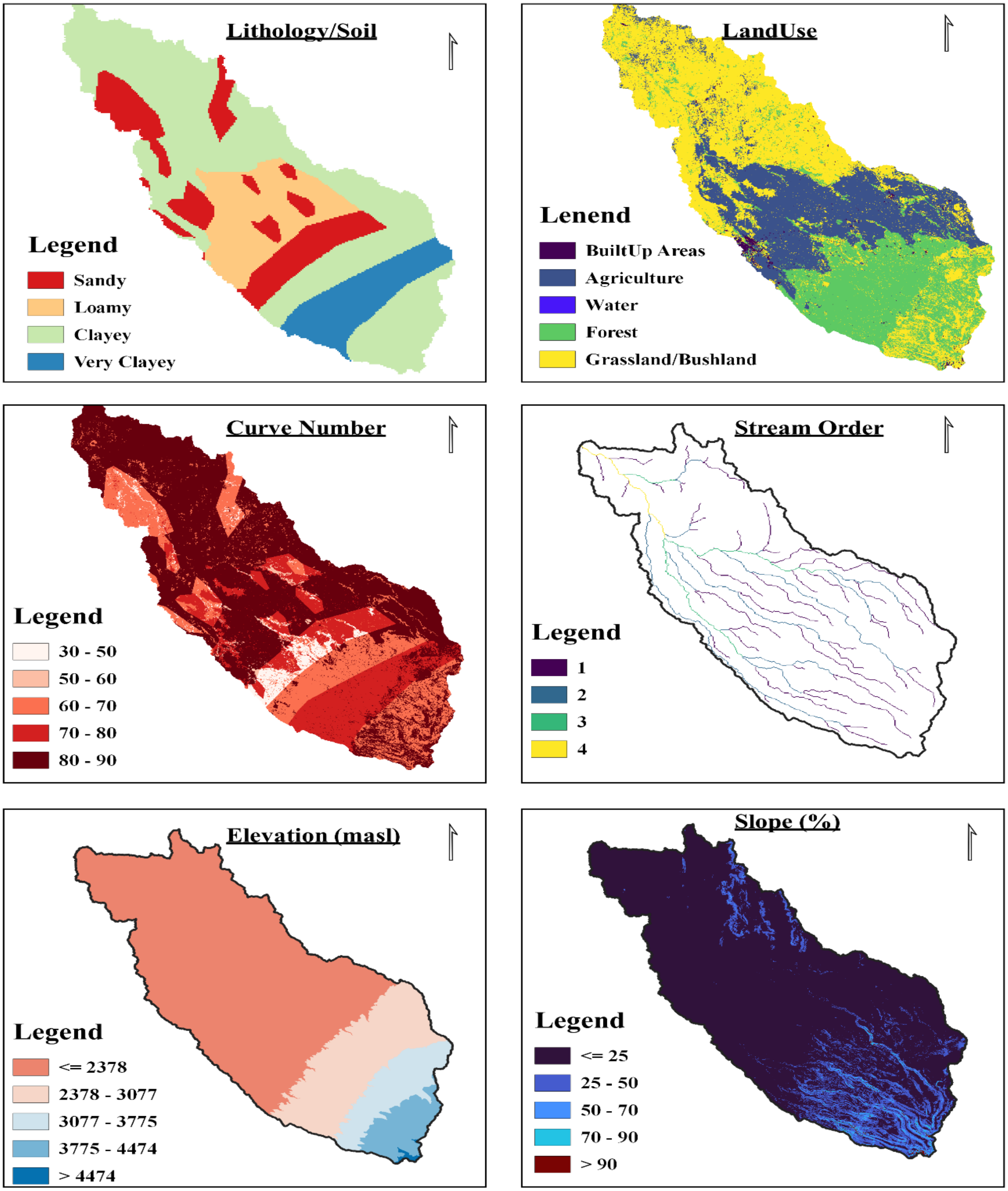
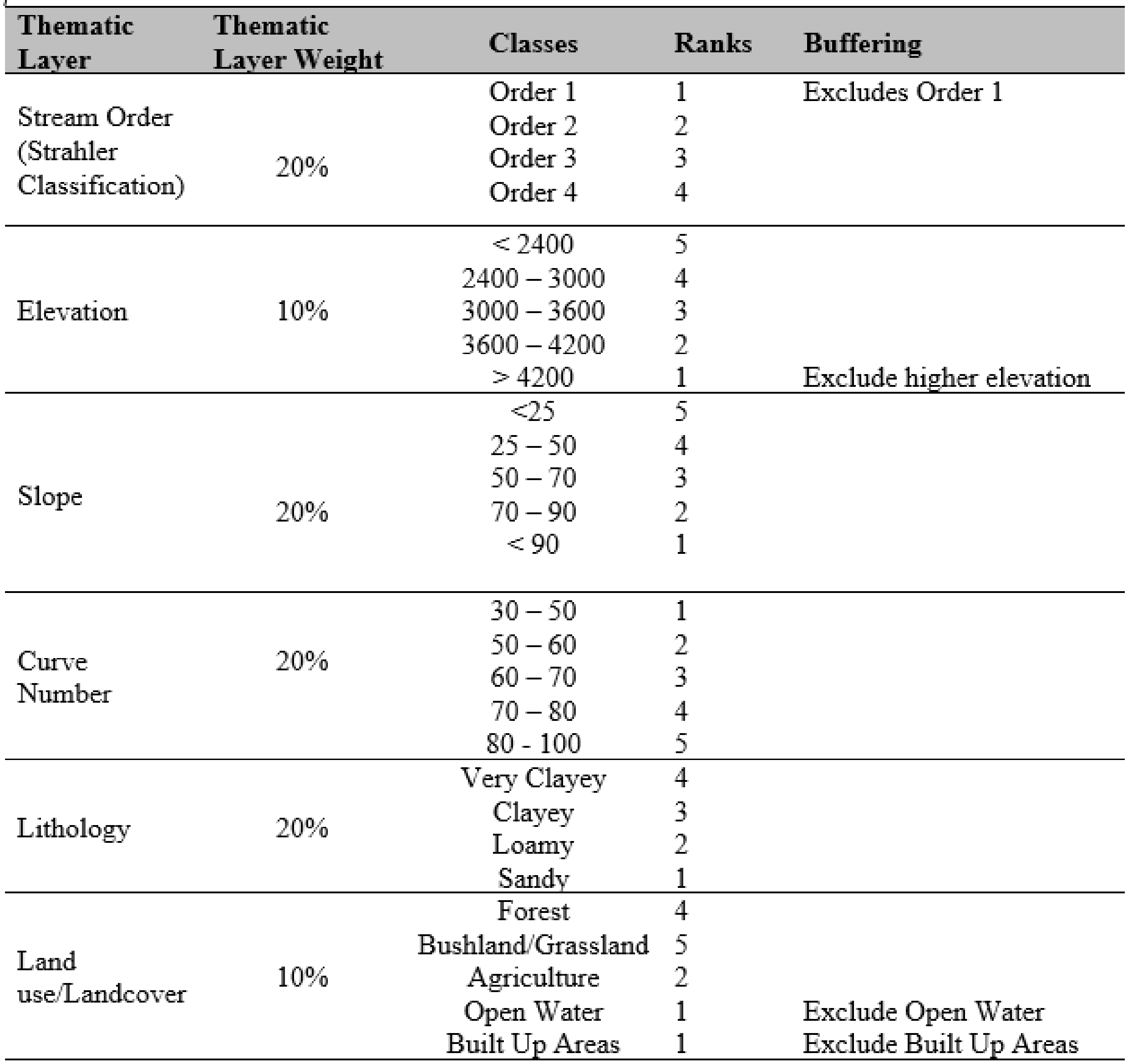


Figure 3-3: Thematic layer maps for the AHP MCDA dam siting method.

Table 3-1: Thematic layers and their subclasses ranking and weighting



Thematic Layer	Thematic Layer Weight	Classes	Ranks	Buffering
Stream Order (Strahler Classification)	20%	Order 1	1	Excludes Order 1
		Order 2	2	
		Order 3	3	
		Order 4	4	
Elevation	10%	< 2400	5	
		2400 – 3000	4	
		3000 – 3600	3	
		3600 – 4200	2	
		> 4200	1	Exclude higher elevation
Slope	20%	<25	5	
		25 – 50	4	
		50 – 70	3	
		70 – 90	2	
		< 90	1	
Curve Number	20%	30 – 50	1	
		50 – 60	2	
		60 – 70	3	
		70 – 80	4	
		80 - 100	5	
Lithology	20%	Very Clayey	4	
		Clayey	3	
		Loamy	2	
		Sandy	1	
Land use/Landcover	10%	Forest	4	
		Bushland/Grassland	5	
		Agriculture	2	
		Open Water	1	Exclude Open Water
		Built Up Areas	1	Exclude Built Up Areas

3.2.2. Reservoir Characteristics

Digital Elevation Model is the key fundamental data for determining reservoir features. Therefore, using a mix of Geographical Information System tools and software, contours were derived from a 30 m ASTER DEM. The area and elevation were established as the important properties since they are essential for establishing an ideal storage size that satisfies the intended water demand. In order to attain the maximum dam storage capacity with the ideal surface area, the ideal height of the crest the sited dams were established. The catchment's semi-arid regions, where there is a large potential for evapotranspiration and consequent open water evaporation, are where the dams are intended to be built. With the aid of GIS, contours were generated for each 2 m rise in elevation from the 30 m resolution DEM so as to calculate the surface area-volume of the reservoir characteristics. A polygon was made taking into account the contours in the upstream direction and the placement of the existing dam as the dam axis. The storage volume at each height was determined using the Cut-and-fill tool. The volume was estimated for each cut/fill pixel at the dam position. The volume formula is as shown below for a single pixel cell.

Volume = Pixel area * ΔZ where:

ΔZ = Z Before – Z after and Z is the elevation above sea level (m).

Since the DEM utilized had a 30 m resolution, the pixels used for the calculation of the net-gain volume had a uniform area of 900 m^2. As a result, areas were estimated and polygons were formed at various heights. Additionally, the elevation at each contour taken into account was indicated. Using the cut and fill tools in ArcGIS 10.3 software, expected flooding areas in the dam axis upstream were extracted and the storage volume at the corresponding contour elevation computed. The contours and top area of the dams at the two optimum locations are shown in Figure 3-4.

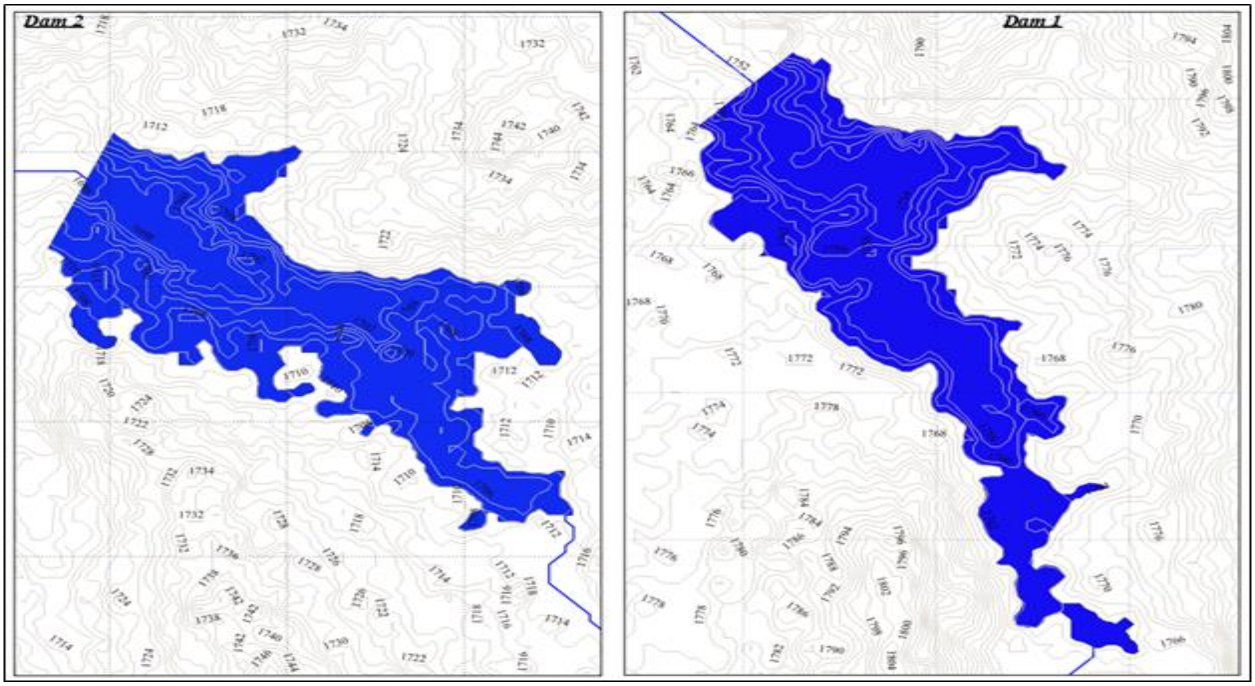


Figure 3-4: Diagram of the dams' top area and curves at the two most ideal places.

3.2.3. Rainfall Runoff Modelling in HMS

3.2.3.1. Datasets

Rainfall and stream flow are among the data used in this study. Due to extensive data gaps that limited adoption of appropriate infilling approaches, satellite derived precipitation was obtained to argument data from ground stations at daily time-steps at the existing station location. Data (rainfall) with a 5.5 km by 5.5 km spatial resolution for the period 1981-2019 at daily time-steps was obtained from the Climate Hazard Centre (http://iridl.ldeo.columbia.edu/SOURCES/.UCSB/.CHIRPS/.v2p0/.daily-improved). CHIRPS-v2 is a global rainfall product with a fairly low latent and bias because of the interpolation between satellite-derived rainfall estimates and the ground gauge data (Muthoni et al., 2018; Rivera et al., 2019). Discharge data was obtained from Water Resources Authority for six river gauging stations having daily data since 1960. Discharge data was used for the calibration and validation of the model output. Table 3-2 provides Summary of RGS in the Nanyuki Catchment Area (ID, Name and Coordinates).

Table 3-2: Summary of RGS in the Nanyuki Catchment Area

Station ID	**River Name**	**Longitude**	**Latitude**
5BE02	Ontulili	37.139	0.040
5BE07	Likii	37.087	0.021
5BE01	Nanyuki	37.077	0.021
5BE20	Nanyuki	37.03	0.147
5BE22	Sirimon	37.20	0.061
5BE06	Timau	37.242	0.088

Monthly Potential Evapotranspiration values were extracted from CLIMWAT FAO database using CROPWAT software (Table 3-3).

Table 3-3: Monthly Probable Evapotranspiration

Month	**Evapotranspiration (mm)**
January	127.72
February	127.96
March	129.89
April	102.9
May	101.37
June	100.8
July	100.44
August	87.11
September	113.1
October	110.67
November	91.5
December	105.4

Source: CLIMWAT FAO database

3.2.3.2. Soil and Land use

QGIS 3.10 and ArcGIS 10.3 were used for visualization and editing of soil and land use data, while Microsoft Excel was employed for analysing and organising precipitation data. The watershed was delineated using the Arc Hydro tool in ArcGIS, which was based on a DEM and river maps. The CN Grid was derived using a GIS based approach (ArcGIS). Rainfall was downloaded using an R statistical package from the Climate Hazard Centre (http://iridl.ldeo. columbia.edu /SOURCES/.UCSB/.CHIRPS/.v2p0/.daily-improved). For the simulation of hydrological processes, the Hydrologic Modelling System (HEC-HMS) was used.

3.2.3.3. HEC-HMS Model Application

The HEC-HMS model components that comprises of basin, meteorology, input data and control specification components that were compiled. The basin element is made up of connected hydrologic elements representing water flow through a drainage system. The meteorological component on the other hand acts as a computational containing observed precipitation (Annex 4.1) and discharge data (Annex 4.2.1 to Annex 4.2.5) distributed spatially and temporarily over the drainage basin. The control specification element regulates the period of simulation and time steps to be adopted. The observed rainfall historical data for stations representing the sub-basins and data for river gauge station 5BE20 were transposed to the outlet and used for calibrating and validating the model.

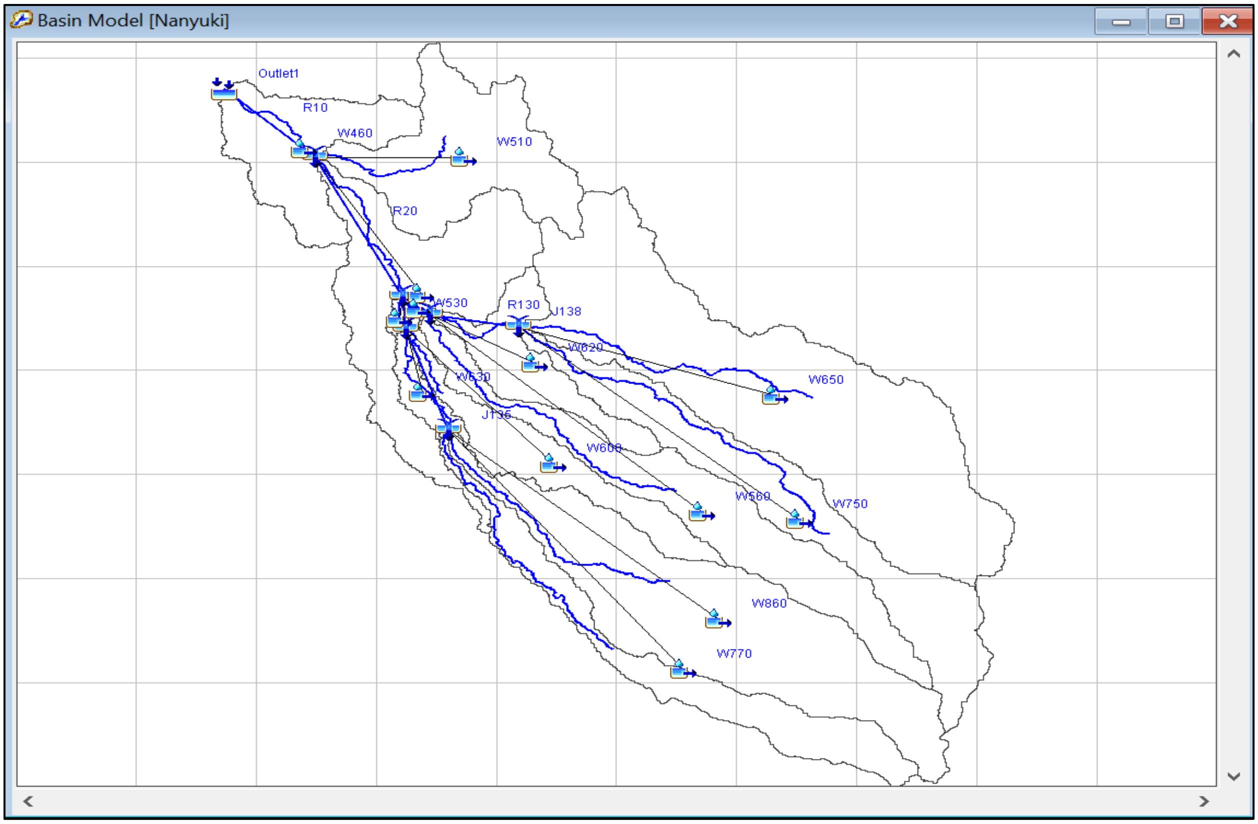


Figure 3-5: River Nanyuki Basin Model.

Taking into account the available observed data's time interval, a daily time step was applied while carrying out the simulation. The ArcGIS tool for delineation of the catchment was used to delineate the watershed based on DEM while the HEC-GeoHMS was employed in the development of the HMS Model (see Figure 3-5). HEC-GeoHMS was used to create basin and meteorological models including the control specifications within the ArcGIS Environment (Fleming & Doan, 2009). The complete model was thereafter imported into HEC-HMS version 3.5 for simulation of the respective hydrological processes. This approach of model development was selected due to its simplicity and accuracy. Infiltration losses were modelled using the Soil Moisture Accounting (SMA) with the HEC-HMS together with canopy and surface methods. With SMA, water is trapped by the canopy leaves, surface depression, the soil profiles and two layers representing groundwater storage. The canopy losses are usually considered as the initial losses and thus infiltration is always subtracted from the infiltration that exceeds the canopy losses. The extra precipitation drips onto the soil's surface through the canopy.

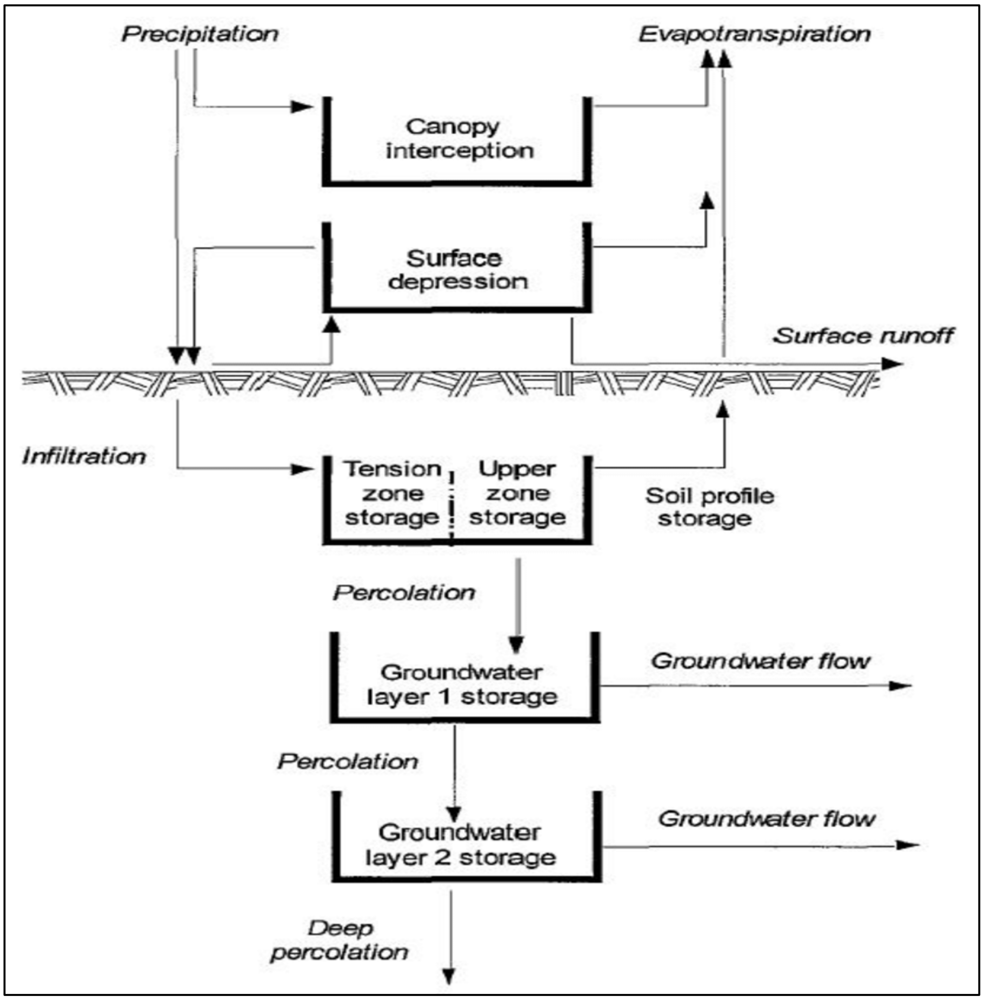


Figure 3-6: Soil Moisture Accounting conceptual framework

Infiltration amount that does not infiltrate accumulates in the surface depressions. Runoff starts after rate of infiltration is exceeded by precipitation and the depressions on the surface depressions are completely filled. Respective values for both the canopy and surface storage adopted in the analysis have been extracted from Land-use and DEM maps as illustrated in Figure 3-6. Tables 3-4 and 3-5 shows the respective input values for canopy and surface depressions.

Table 3-4: Canopy Interception Values

Vegetation Type	Interception Value (mm)
General Vegetation	1.270
Deciduous Trees and Grasses	2.032
Coniferous Trees	2.540

Table 3-5: Storage Values for Surface Depressions

Surface Characterization	Slope (Percentage)	Storage Value (mm)
Impervious surface	NA	3.18-6.35
Steep surface	>30	50.8
Moderate to gentle surface	5-30	6.35-12.70
Flat or furrow surface	0-5	1.02

The study considered 12 parameters indicated in Table 3-6 as required by the SMA Loss Method. Maximum infiltration rate, maximum soil depth, percolation rates and components representing groundwater played a significant role on the rainfall-runoff simulation. For each sub-catchment, the percentage of area under development from google images QGIS was designated as impervious. The measure of water stored in the soil was defined as the porosity also defined as the space in the soil available for water to occupy as shown in Table 3-7. Other parameters were adjusted such that the model's simulated discharge matches the observed discharge. SMA approach was used for accounting canopy retention and simulation of percolation of water to ground water storage. All of these layers have soil moisture wet and dry cycles, allowing for a long-term continuous hydrological simulation. The transform model simulates and transforms excess precipitation to direct runoff for specified watersheds. This study adopted the Soil Conservation Service (SCS) Unit Hydrograph as the transform parameter. SCS unit hydrograph transforms excess rainfall to runoff using lag time as the input. Lag time (T_{lag}) which is calculated based on time of concentration (T_c) refers to the time from the centroidal mass of rainfall excess to the hydrograph peak. The time of concentration was estimated based on the below empirical model:

$$T_{lag} = L^{0.8} (S + 1)^{0.7} /(1900\sqrt{Y}) \text{ and } S=254/CN-254$$

Where:
T_{lag} is the lag time in hours
L is the hydraulic length of the watershed in feet
S is the maximum retention in the watershed in mm
CN is the watershed SCS curve number
Y is the watershed slope in percentage

Base flow was modelled with linear reservoir method (Abushandi & Merkel, 2013) with a consideration of the following parameter requirements:

- Groundwater 1 initial (m^3/s): original base flow on the beginning of the simulation for the top groundwater layer.
- Groundwater 1 coefficient (h): Comeback time for the sub-basin.
- Groundwater 1 reservoir - Base flow directed through numerous successive reservoirs.

Linear Reservoir baseflow method adopts three linear reservoirs or layers to simulate the baseflow recession. Base flow is reduced with increase in the quantity of the reservoirs. Identical parameters are also definite of the groundwater's second layer.

Table 3-6. Showing SMA model parameters

Canopy	Initial canopy storage (%) Maximum canopy storage (mm) Crop coefficient
Surface	Initial surface storage (%) Maximum surface storage (mm)
Soil Moisture Accounting	Soil (%) Ground water 1 (%) Ground water 2 (%) Max infiltration rate (mm/h) Impervious (%) Soil storage (mm) Tension storage (mm) Soil percolation (mm/h) GW 1 storage (mm) GW 1 percolation (mm/h) GW 1 coefficient (h) GW 2 storage (mm) GW 2 percolation (mm/h) GW 2 coefficient (h)

Table 3-7: Soil textures and properties

Sub-basin /Area (km^2)	Soil Texture	Slope (%)	Basin Lag (Hours)	Saturated Hydraulic Conductivity (cm/hour)	Bulk Density (g/cm^3)	Porosity (%) (cm^3/cm^3) *100
W460 (60.06)	Clay	4.98	4.02	0.37	1.0	33-60
	Sandy			6.34	1.6	25-50
W500 (111.83)	Clay	6.78	5.61	0.37	1.0	33-60
	Sandy			6.34	1.6	25-50
W510 (97.90)	Clay	10.20	3.34	0.37	1.0	33-60
	Sandy			6.34	1.6	25-50
W530 (2.79)	Clay	5.53	1.36	0.37	1.0	33-60
	Sandy			6.34	1.6	25-50
W550 (1.86)	Clay	5.56	0.71	0.37	1.0	33-60
	Sandy			6.34	1.6	25-50
W560 (104.37)	Clay	13.28	6.07	0.37	1.0	35-50
	Loamy			2.50	1.4	20-35
	Sandy			6.34	1.6	25-50
	Very-clayey			0.46	1.1	33-60
W600 (50.47)	Clay	6.45	6.06	0.37	1.0	35-50
	Loamy			2.50	1.4	20-35
	Sandy			6.34	1.6	25-50
W620 (44.22)	Clay	6.37	3.09	0.37	1.0	35-50
	Loamy			2.50	1.4	20-35
	Sandy			6.34	1.6	25-50
	Very-clayey			0.46	1.1	33-60
W630 (12.28)	Clay	4.47	2.60	0.37	1.0	33-60
	Sandy			6.34	1.6	25-50
W650 (269.08)	Clay			0.37	1.0	35-50

Sub-basin /Area (km^2)	**Soil Texture**	**Slope (%)**	**Basin Lag (Hours)**	**Saturated Hydraulic Conductivity (cm/hour)**	**Bulk Density (g/cm^3)**	**Porosity (%) (cm^3/cm^3) *100**
	Loamy	11.39	4.50	2.50	1.4	20-35
	Sandy			6.34	1.6	25-50
	Very-clayey			0.46	1.1	33-60
W750 (112.55)	Clay	16.47	4.92	0.37	1.0	35-50
	Loamy			2.50	1.4	20-35
	Sandy			6.34	1.6	25-50
	Very-clayey			0.46	1.1	33-60
W770 (73.29)	Clay	23.60	3.98	0.37	1.0	35-50
	Loamy			2.50	1.4	20-35
	Sandy			6.34	1.6	25-50
	Very-clayey			0.46	1.1	33-60
W860 (182.27)	Clay	22.42	4.57	0.37	1.0	35-50
	Loamy			2.50	1.4	20-35
	Sandy			6.34	1.6	25-50
	Very-clayey			0.46	1.1	33-60

3.2.3.4. Calibration and Validation

Hydrologic model calibration and validation are performed to generate model outputs that are reliable. This is done using sets stream flow data obtained from observation. The simulated stream flow is usually compared with observed stream flow and goodness of fit evaluated to establish level of accuracy in the model prediction. The model used in the study was calibrated based on identified parameters and a perfect match tested between the simulated data and the observed data. Distinct selected parameters were varied through automatic calibration using optimization tools available in the HEC-HMS model. The search method utilized for optimization was the Nelder-Mead simplex method because it would allow several parameters to be optimized. The optimization procedure in the HEC-HMS does not always produce the desired best parameter values and thus the need for manual calibration which was performed. Several objectives function in relation to the key parameters that determine model performance were adopted in shifts to bring the model near to reality. The validation process involved the use of improved parameters at varying periods and thereafter verifying the resultant goodness of fit between the simulated and observed stream flow data.

3.2.3.5. Model Performance Evaluation

The efficiency of the HEC-HMS model was assessed using the following parameters to assess the degree of similarity between simulated and real stream flow (Jin et al., 2015).

1. The Percentage Error in Peak Flow (PEPF) - The PEPF takes into account the magnitude of the computed peak flow but ignores the total volume or timing of the peak.

$$PEPF = 100\left|\frac{Q_0(peak) - Q_S(Peak)}{Q_O(peak)}\right|$$

Where:
Q_O is the observed flow.
Q_s is the simulated flow.

2. Percentage Error in Volume (PEV) -: The PEV function only takes into account the measured volume and ignores the magnitude and timing of the peak flow.

$$PEV = 100\left|\frac{V_o - V_S}{V_O}\right|$$

Where:
V_O is the volume of the observed hydrograph
V_S is the volume of the simulated hydrograph

3. Coefficient of correlation (R). The lag-0 cross correlation coefficient was calculated as:

$$R = \frac{\sum_{t=1}^{N}(Q_t - \bar{O}) \times (S_t - \bar{S})}{\sqrt{[\sum_{t=1}^{N}(O_t - \bar{O})^2 \times \sum_{t=1}^{N}(S_t - \bar{S})^2]}}$$

Where:
O_t is the observed flow at time t
S_t is the simulated flow at time t
O is the average observed flow during the calibration period.
S is the average simulated flow during the calibration period.

4. The Relative Root Mean Squared Error (RRMSE) calculated as:

$$RRMSE = 100 \times \sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(\frac{S_t - O_t}{O_t}\right)^2}$$

Where:
N is the number of streamflow ordinates
O_t is the observed flow at time t
S_t is the simulated flow at time t

5. The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that measures the magnitude of residual variance in comparison to calculated data variance. The Nash-Sutcliffe efficiency of a plot of observed versus simulated data shows how well it matches the 1:1 axis.

$$NSE = 1 = \frac{\sum_{i=1}^{n}(OBS_i - SIM_i)^2}{\sum_{i=1}^{n}(OBS_i - \overline{OBS})^2}$$

To interpret the results, parameter ranges illustrated in Table 3-8 were used as a guide.

Table 3-8. General performance ratings for recommended statistics

SI. No.	Performance Rating	PEPF (%)	PEV (%)	NSE	R^2
1	Very Good	<15	<±10	0.75 – 1.00	0.75 - 1
2	Good	15 - 30	±10 - ±15	0.65 – 0.75	0.65 – 0.75
3	Satisfactory	30 – 40	±15 - ±25	0.50 – 0.65	0.50 – 0.65
4	Unsatisfactory	>40	±25	<0.50	<0.50

3.2.3.6. Sensitivity Analysis

It is critical to identify parameters of high influence in rainfall-runoff modelling; this is achieved through Sensitivity analysis. Optimized parameters are usually replaced in the model to achieve the desired output. Sensitivity of the optimized parameters vary. Sensitivity analysis was done on three parameters of the model. The final parameter set from model calibration were considered as baseline. The calibrated model was run several times, beginning with the baseline value for each individual parameter multiplied by 0.7, 0.8, 0.9, 1.1, 1.2, and 1.3. The hydrographs generated by the modified model parameter scenarios were compared to the baseline model hydrograph.

3.2.4. Water Resource Planning using WEAP

3.2.4.1. Water Abstraction data

Water shortage in the Nanyuki River Basin is primarily due to increase in water abstraction activities (Aeschbacher et al., 2005). Thus, quantifying the temporal water abstraction is fundamentally critical for this study. The abstraction data was acquired from Water Resources Authority, the Nanyuki office (Table 3-9). The data only covers the Nanyuki stream representing a range of abstractors, amount abstracted and water uses.

Table 3-9: List of water abstractors

Abstractor	**Category**	**Q.O.W (m^3/day)**	**Population Served**	**Water Use**
Kaga Water Project	C	961.92	5962	NIL
Maka Green Growers Self Help Group	B	133.2	1650	Domestic and Commercial Irrigation
Huku Water Project	C	1692	600	Domestic and Subsistence Irrigation Use
Mwea B Water Project	B	47.7	1850	Domestic Use
Derek Holmes	B	79	80	Abstracting Water for Domestic and Subsistence Irrigation
Stephene Muriungi Kiambati	A	15.87	20	Domestic and Subsistence Irrigation
William Holden Wildlife Foundation	B	50	60	Pumping Water for Subsistence Irrigation and Domes
Mt. Kenya Game Ranch Limited	B	51.25	25	Pump, Delivery Pipe and Pan for Domestic and Wild
Ruai Water Project	B	101.15	2250	Weir 1m High, Gravity Line for Dom. Water Only
James Gachai Nduhiu	A	1.43	0	Water or Flowers and Lawn
Alick G. And Deirdre J. R	A	4.44	60	Pumping for Domestic Use Only
Sajjad Mahamud Butt	A	10	150	Surface Water Abstraction for domestic Use Only

Abstractor	Category	Q.O.W (m^3/day)	Population Served	Water Use
Linkline Investment Ltd	A	20	150	Surface Water Abstraction for Domestic Water Use
Lairagwan Limited	A	2	12	Pumping Water for Domestic and Kitchen Gardening
Westbuild (General Contractor)	B	55	300	Pumping Water into a Tanker for Road Construction
Rael Gacheri Muriugi	B	190	0	Collection Box (2.3 X I.0 X0.5) M And 2" Gravity Line for Domestic and Irrigation
Wambui Kamau	A	19	10	Surface Water Abstraction for Domestic and Minor I

3.2.4.2. WEAP Model Development

For one to make sound water allocation decisions, one must be able to estimate spatial and temporal changes that occur in the availability of water under the various climatic conditions. WEAP model provides the important methods that are required for planning of water resources and this was the reason that it was selected for this study. Water balance being the key focal point of WEAP, one can apply it to single catchments which are simple or to transboundary river catchments which are complex, and can also be applied in agricultural and municipal systems. WEAP is able to distinguish a “business as usual” scenario from alternative policy scenario. In this study, the “business as usual” scenario is taken as the reference scenario and includes the trends currently in demographic and economic development, the available water supply resources, the efficiency in water usage and the policies that govern water pricing. It is against this “business as usual” scenario that alternative policy's consequences scenario will be analyzed. A WEAP model schematic diagram for the Nanyuki river shows the demand site with the available sources of water such as streams and dams. Two main scenarios were considered in the assessment, with dams and without dams. The WEAP model developed included a single reach, an abstraction location, two reservoirs, and an assumed theoretical baseline demand side of 3 m^3/s. The demand was increased to 4.5 m^3/s and 6 m^3/s subsequently for the two scenarios as illustrated in figure 3-7. (WEAP model developed that included a single reach, an abstraction location, two reservoirs, and an assumed theoretical demand side 6 m^3/s). Although, the demand was assumed to be equal throughout the year, it tends to vary in the actual sense. No irrigation occurs during the rain seasons. The existence of reservoir modifies downstream flows depending on the operational rule curve. The two reservoirs implemented in the model were assumed to operate on a rule curve of maintaining certain threshold of downstream flows. Plate 3-2 shows the Ewaso Ng’iro river at Archer’s Post.

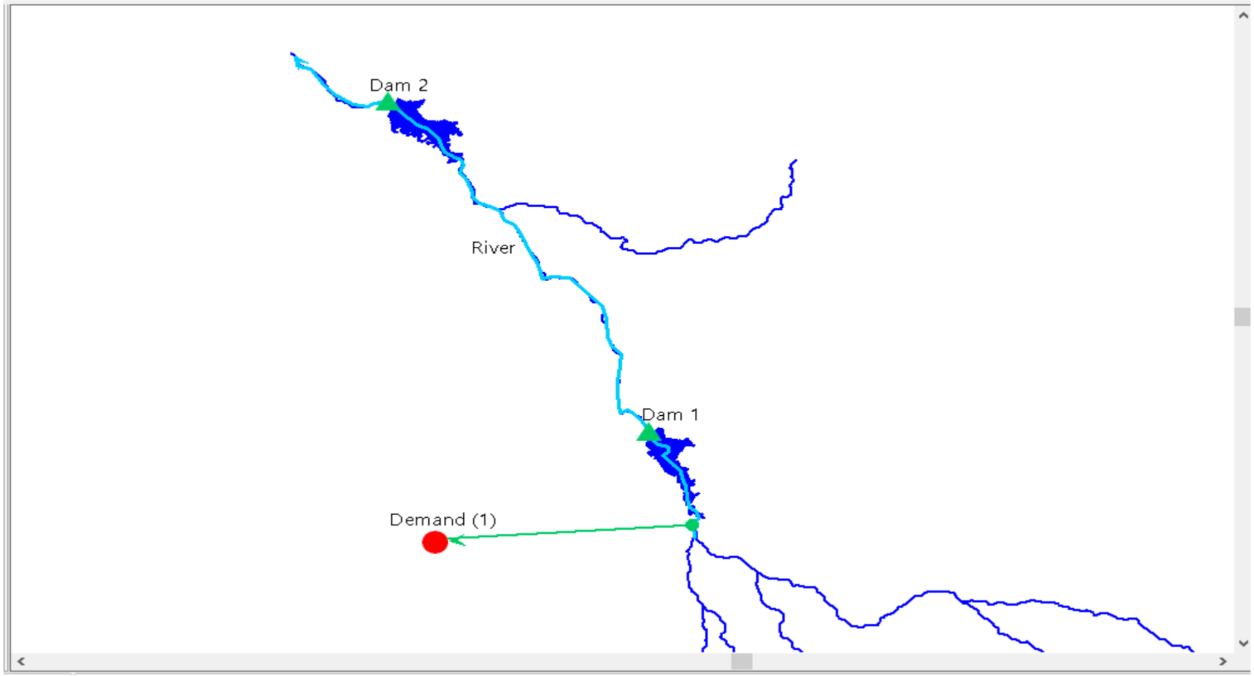


Figure 3-7: WEAP model.

Plate 3-2: Ewaso Ng'iro river in Archer's Post.

4. RESULTS AND DISCUSSIONS

4.1. Dam Siting and Reservoir Characteristics

Figure 4-1 is map of dam suitability sites. There are locations ideal for dam sites upstream of the river, but due to the sharp slope and the need for dams for residents downstream, it was determined that two locations illustrated are the most acceptable locations.

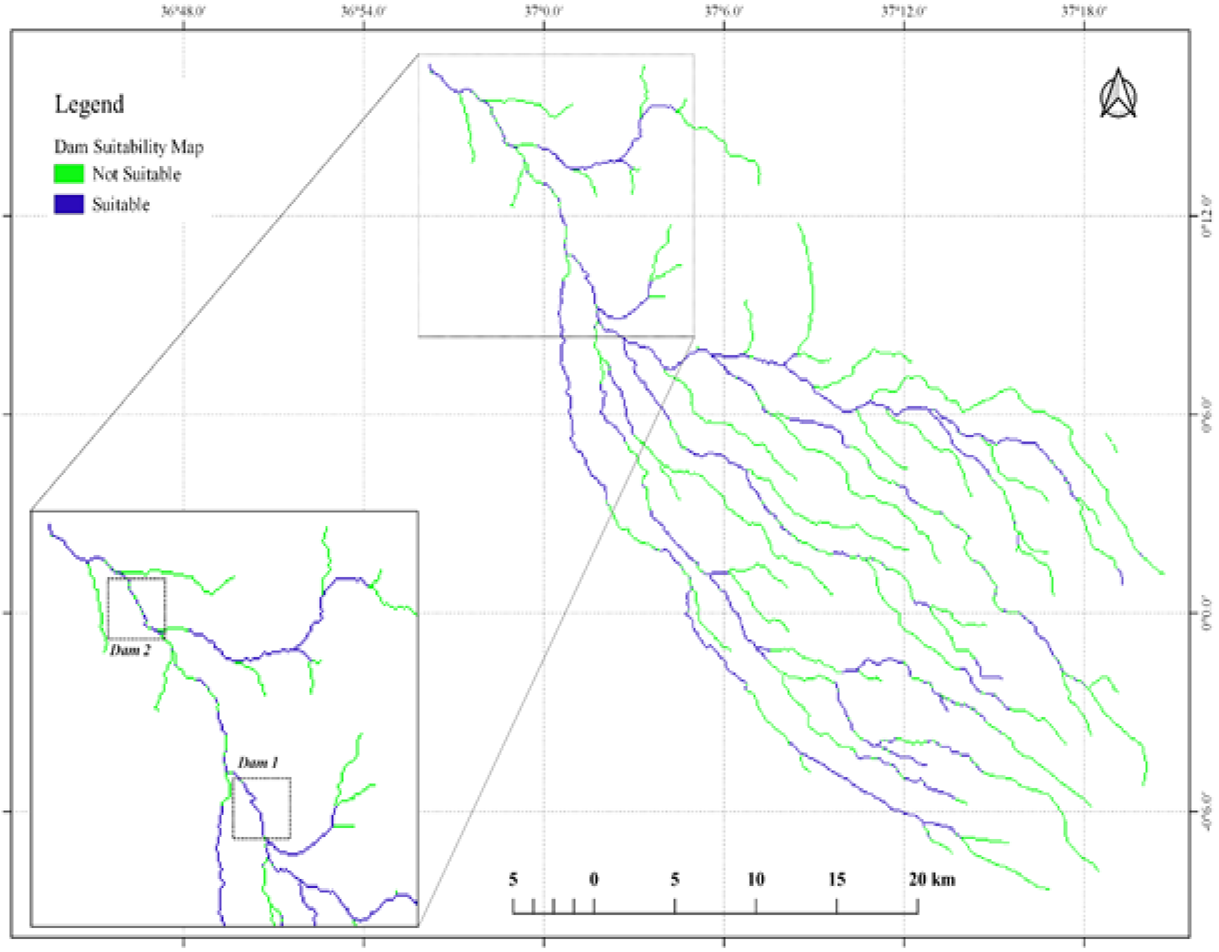
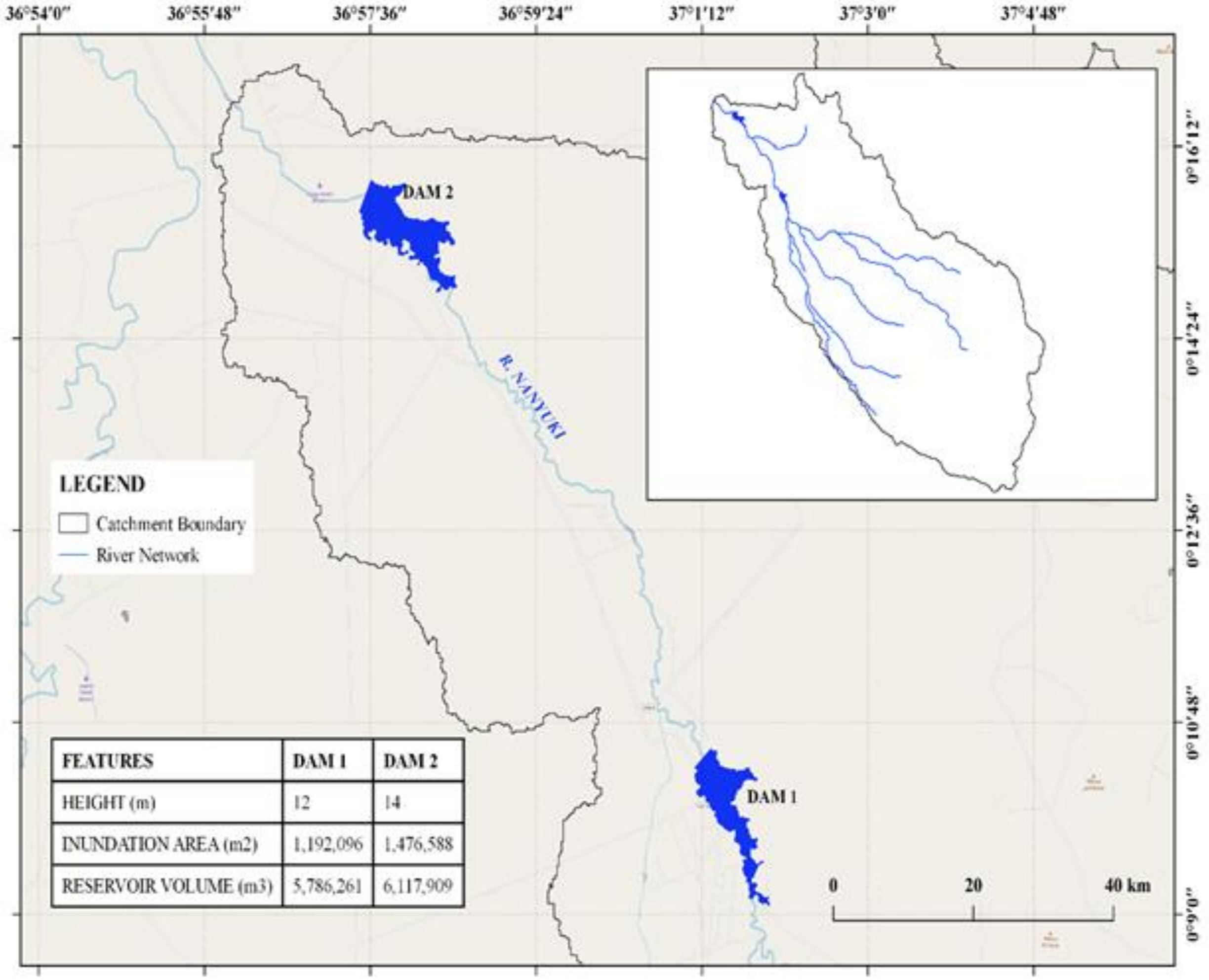


Figure 4-1: Dam Suitability Map

Two of the dams situated along the major river reach were taken into account in the evaluation, as shown in Figure 4-2. The dam axis cross-section of two selected locations are shown in Figures 4-3 and 4-4. The fetch for dam 1 is 2800m and for dam 2 is 3400m. Any scale of dam's location must take safety, the environment, and economy into account. Thus, environmental, physical, and economic settings should all be taken into consideration when deciding where to site any dam. The speedy identification of the best reservoir locations, which is essential for planning and decision-making processes, can be accomplished with the help of geographic information systems and remote sensing. The relevant sites were chosen because they were away from the settlements but close to the target users in the grazing lands and in active year-round agricultural zones. This ensured minimal conflicts between the farmers and pastoralists in the upstream areas of the catchment. In general, the potential sites chosen meet the criteria's constraints.



FEATURES	DAM 1	DAM 2
HEIGHT (m)	12	14
INUNDATION AREA (m2)	1,192,096	1,476,588
RESERVOIR VOLUME (m3)	5,786,261	6,117,909

Figure 4-2: Setting of the maps that were taken into account for modelling the effect of small dams on downstream flows.

While GIS and RS-based technique enables a quick, more objective decision-making process, there is a still a certain amount of subjectivity involved in allocating weights and scaling layers. If there is enough time, ground truthing should be used to verify if the results of the MCDA procedure for dam siting are consistent with the actual site reality.

[A]

maximum 1763.89

minimum 1750.11

☑ Interpolated profile

Selection: Temporary polyline

☑ Show cursor

☑ Link mouse position on graph with canvas

[B]

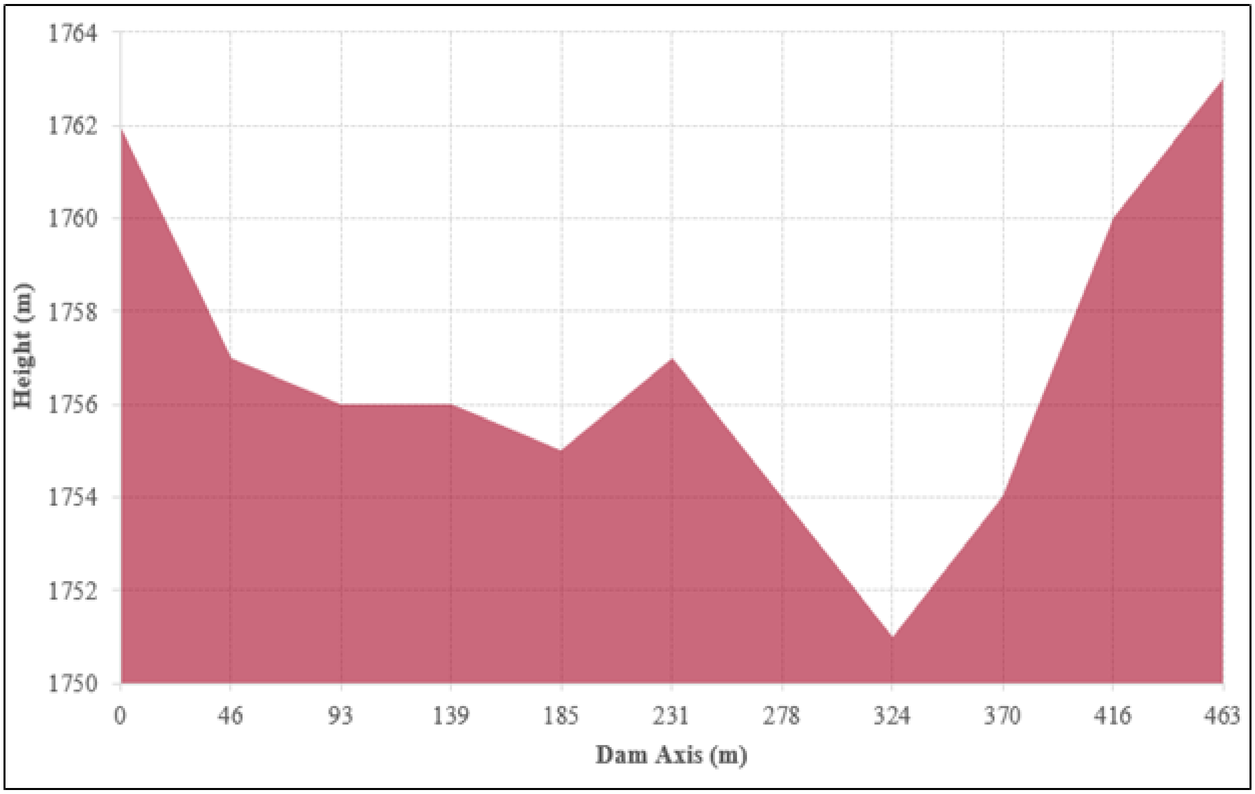
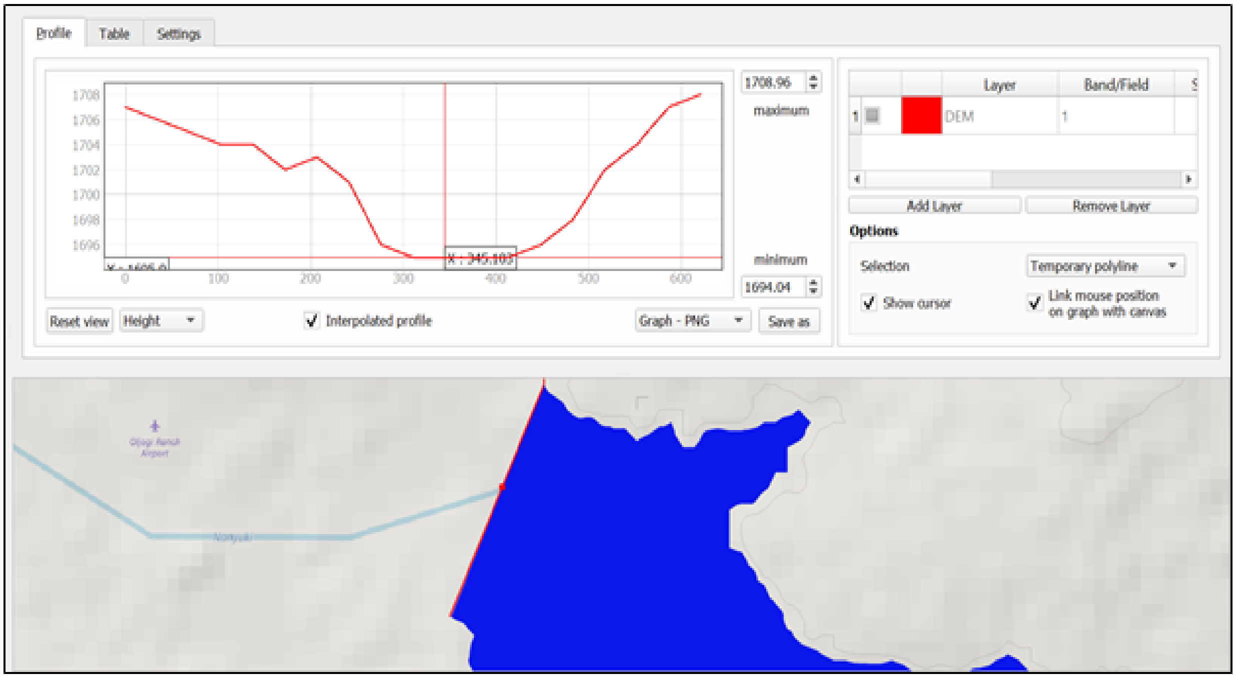


Figure 4-3: a) Outline of Dam 1 axis. b) Excel profile plot for dam 1 axis
[A]



maximum 1708.96

minimum 1694.04

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[B]

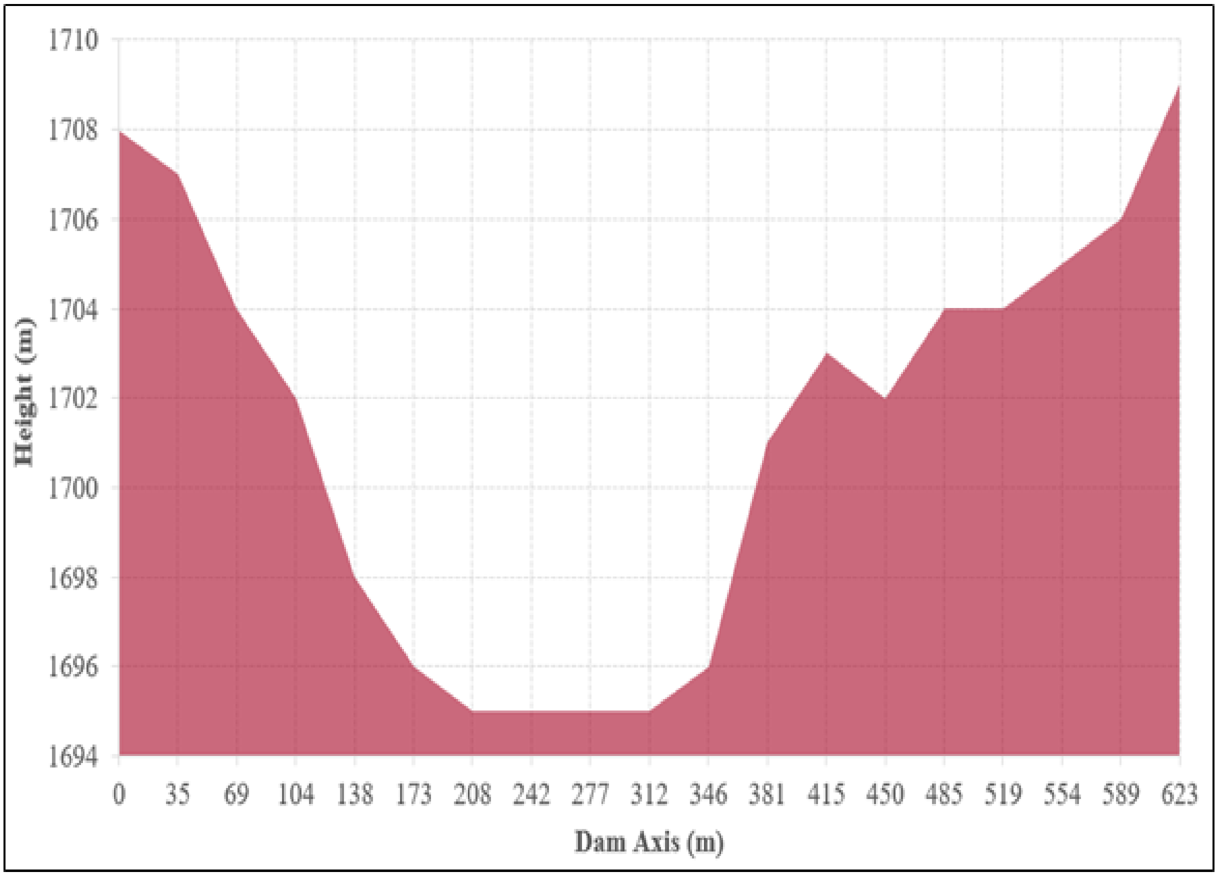

Figure 4-4: a) Outline of Dam axis at site 2. b) Excel Profile for dam 2 axis

The elevation of the dam axis for Dam 1 is 1750 meters (dam width: 460 meters), and that of Dam 2 is roughly 1694 meters (width of 600 m). For Dams 1 and 2, the predicted water storage volumes are 5.8 and 6.1 Mm^3, respectively. Since Dam 1's top water level is 1762 meters above sea level, its height is 12 meters. At an elevation of 1708 meters, Dam 2's height is 14 meters high. This study largely focuses on how modest dams affect downstream flows, the chosen dam however does not fit in the International Commission on Large Dams' definition of a large dam (ICOLD) that states, a major dam must meet the following requirements: a spillway with a minimum potential discharge of 2000 m/s; a dam height of 15 m or above; or a height varying between 10 m and 15 m with a crest above 500 m. The two dams fall outside the definition of a big dam under the ICOLD criteria. The Federal Emergency Management Agency (FEMA) also categorizes dams according to their storage capacity and effective height, as shown in Table 4-1a below.

Table 4-1a: Classification of Dam size in terms of effective height and storage

Sizes	Height effective (feet) X Storage effective (acre-feet)	Height effective
Small	≤3000 acre-feet2	and ≤35 feet
Intermediate	>acre-feet2 and <30000 acre-feet2	or >35 feet
Large	≥30000 acre-feet2	Regardless of the height

The depth, volume, and catchment area are the three variables used by the Water Resource Management Rules (2007) to classify hazards. Three sorts of dams are produced by the method, as indicated in Table 4-1b. The element that puts the dam in the greatest hazard class is dominant. The classification scheme follows the ICOLD scheme. Based on the classification, the dams fall in both class B and C.

Table 4-2b. Dam Size Classification

Class of Dam	Maximum Depth of water at NWL (m)	Impoundment at NWL (m^3)	Catchment Area (km^2)
A (Low Hazard)	0 – 4.99	<100,000	<100
B (Medium Hazard)	5.00 – 14.99	100,000 to 1,000,000	100 to 1,000
C (High Hazard)	➢ 15.00	>1,000.000	>1,000

NWL = Normal water level

According to the aforementioned classification, the situated dams belong to the category of intermediate dams. Figures 4-5 and 4-6, Tables 4-2 and 4-3 indicated the area-volume-elevation relationships for the two identified dam sites.

Table 4-3: Area-Volume-Elevation Curve for the identified Dam No. 1 site

Elevation	Reservoir Area (m^2)	Reservoir Volume (m^3)
1,750	0	0
1,752	16,570	24,707
1,754	197,217	410,521
1,756	421,183	907,518
1,758	626,354	2,200,851
1,760	877,100	3,612,968
1,762	1,192,096	5,786,261

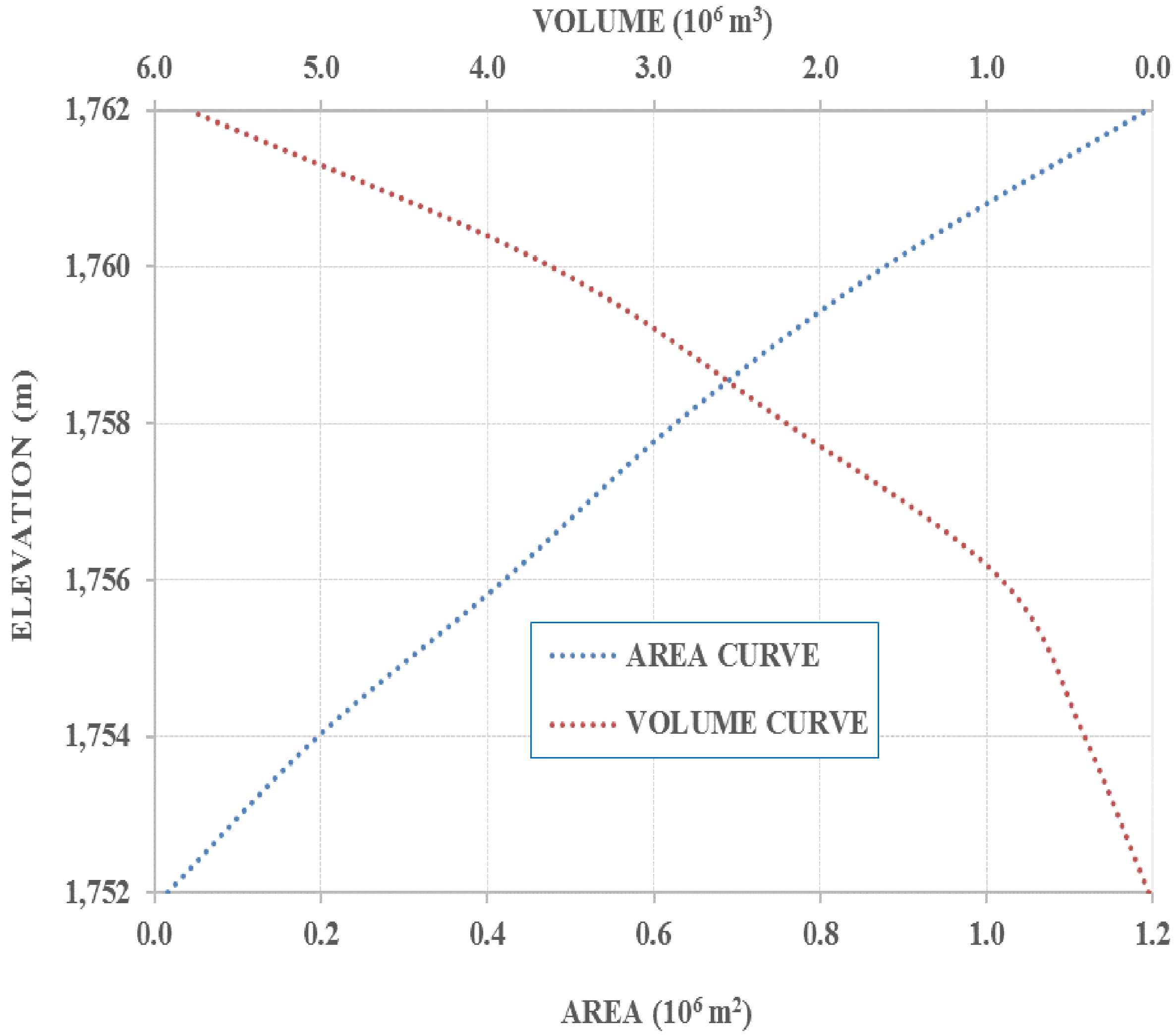

Figure 4-5: Area-Volume-Elevation Curve for the identified Dam No. 1 site

Table 4-4: Area-Volume-Elevation Curve for the identified Dam No. 2 site

Elevation	Reservoir Area (m^2)	Reservoir Area (m^3)
1,694	0	0

1,696	48,249	33,260
1,698	142,599	268,930
1,700	208,603	607,230
1,702	384,743	1,285,730
1,704	563,938	2,170,442
1,706	965,052	3,717,499
1708	1476588	6,117,909

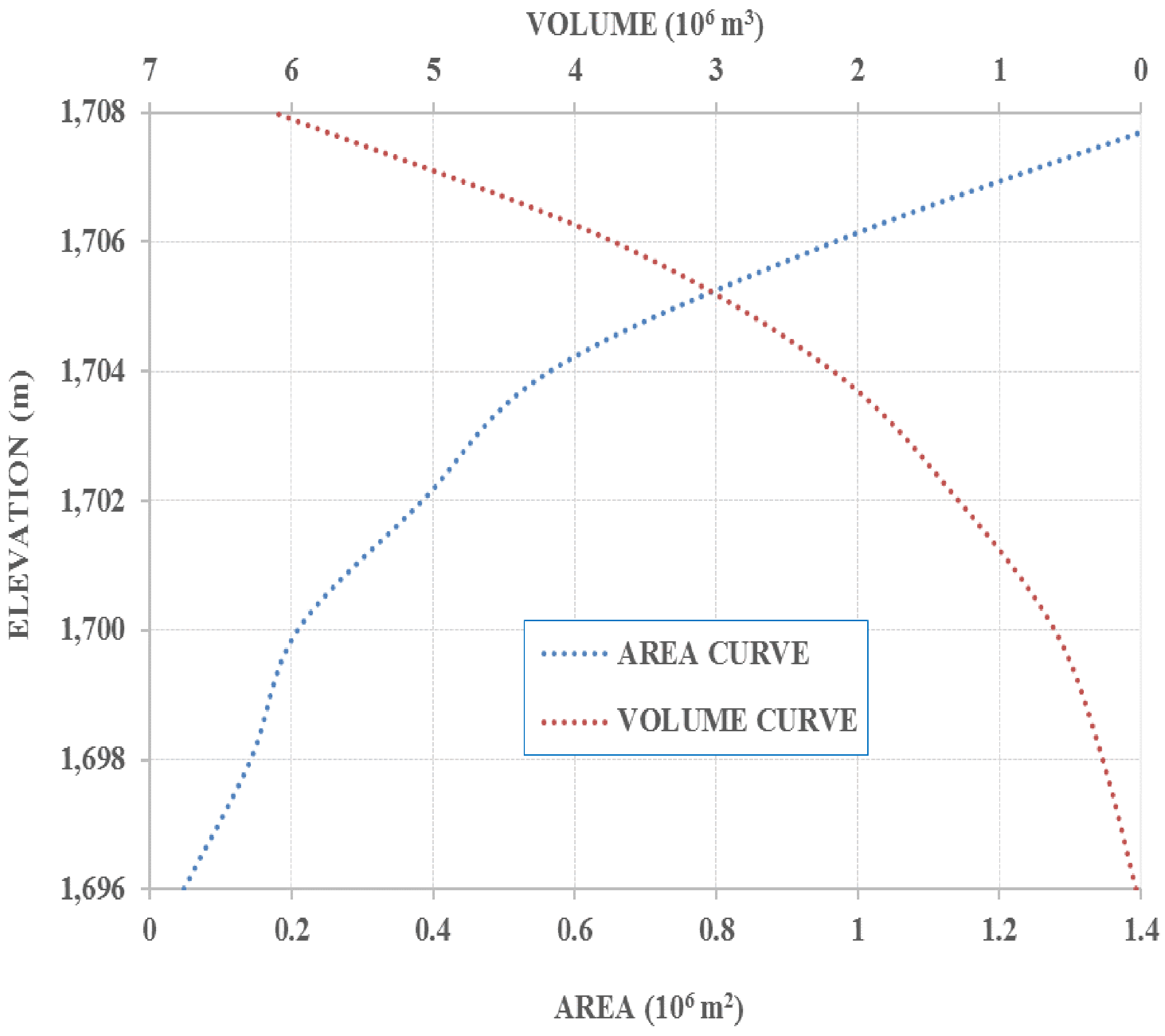

Figure 4-6: Area-Volume-Elevation Curve for the identified Dam No. 2 site

4.2. Rainfall-Runoff Modelling

4.2.1. Calibration and Validation

Ten HEC-HMS parameters were calibrated manually using streamflow data from gauging station 5BE20 transposed to the outlet from 2001 up to 2005.The basic values that were used for the calibration were the same ones for sensitivity analysis. Manual adjustments were made to these values until a reasonable match between simulated and observed stream flows was achieved. Hydrograph visualization and computed statistics values were used to assess the perfect match's quality. Figure 4-7 displays comparison graphs of observed and simulated stream flow for the time period used for calibration (starting from 2001 up to 2005). Comparing the observed stream flow and the simulated stream flow showed a close pact on the subject of peak values and flow distribution in a stream. Optimization of the parameters was done to achieving greater consensus between the observed stream flow and the simulated stream flow.

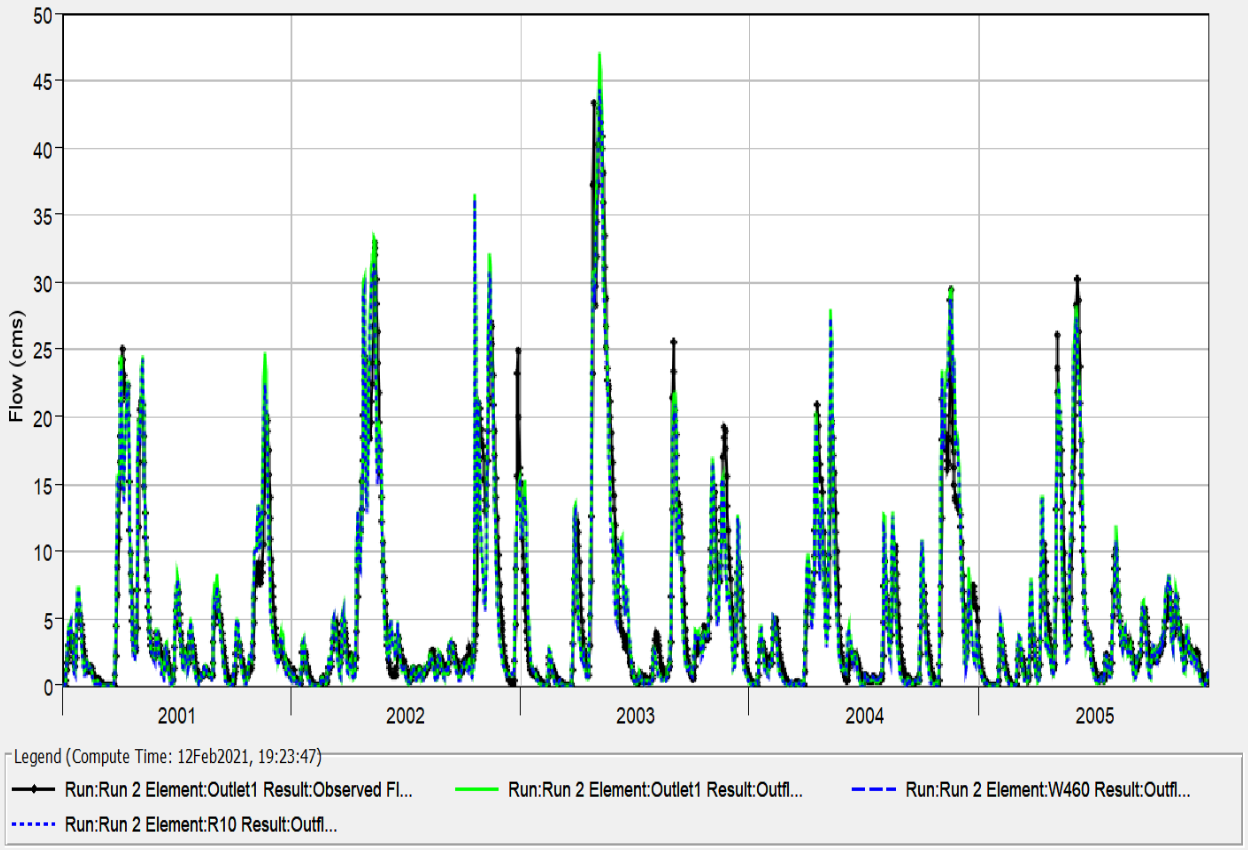

Figure 4-7: Observed and simulated discharges on a regular basis (2001 – 2005)

The model was then validated by running the same input parameters that were used during calibration. The validation was carried out for the period starting from 2006 up to 2007 based on the optimized parameters, to determine the model's ability to predict runoff at the 5BE20 gauging station. Figure 4-8 shows the comparison graphs for the observed and simulated stream flow for the period of validation (2006 to 2007). According to the contrast, the simulated and observed stream flows have a good agreement in terms of peak value and stream flow distribution.

4.2.2. Evaluation of the Model Performance

Each year, as well as the calibration and validation cycles, a continuous model performance assessment took place. Simulation of the HEC-HMS model gave the time series for the simulated and observed flows. The time series were further analyzed using the Microsoft excel in order to calculate the figures that were used for performance evaluation. The figures used were earlier presented in section 3.2.3.5. Similarly, Table 3-8 presented the performance ratings of these parameters. The values of the PEV, PEPF, R^2, NSE and RMSR were found to be 0.49%, 8.55%, 0.86, 0.85 and 0.40, respectively during the calibration. During validation, the values PEV, PEPF, R^2, NSE and RMSR were found to be 0.13%, 24.11%, 0.80, 0.64 and 0.60, respectively. These were for the 5BE20 transposed to the outlet.

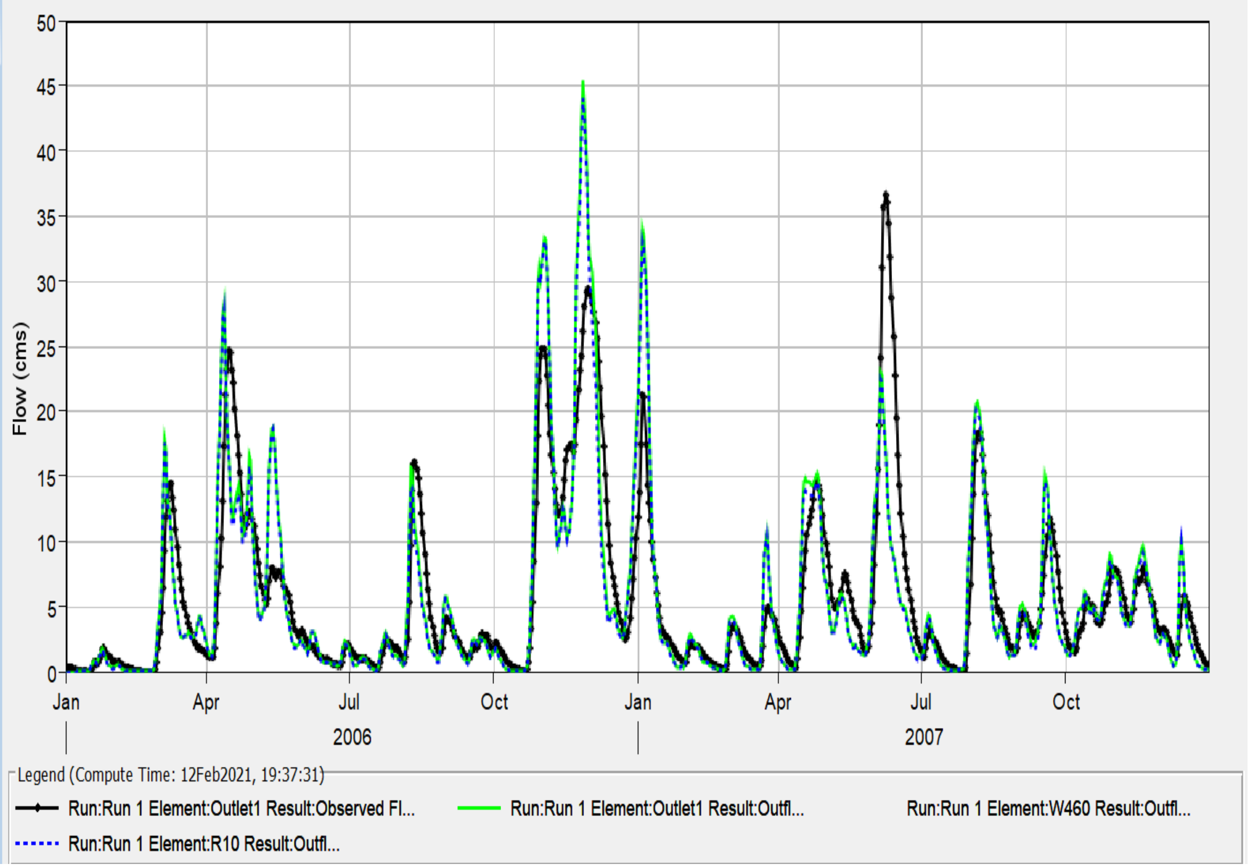

Figure 4-8: Observed and simulated discharge on a regular basis (2006– 2007)

Table 4-4 shows model performance evaluation for specific years for both calibration and validation periods. Model performance varies between satisfactory and very good, except for 2006 and 2007. The variation in the two years is mainly due to various uncertainties measured discharge data. According to the results and calculated statistics (NSE, PEPF, PEV and R^2), the model performance can be assumed to be satisfactory.

Table 4-5: Performance evaluation of the continuous HEC-HMS model

Year	**PEV (%)**	**PEPF (%)**	**NSE**	**R2**	**RMSE**
2001	6.57	0.80	0.85	0.92	0.40
2002	1.29	11.21	0.85	0.89	0.40
2003	9.53	8.55	0.77	0.94	0.50
2004	2.71	0.00	0.78	0.92	0.50
2005	0.87	6.60	0.88	0.94	0.30
2006	6.57	54.76	0.63	0.88	0.60
2007	19.64	36.89	0.47	0.72	0.70
Calibration	0.49	8.55	0.85	0.86	0.40
Validation	0.13	24.11	0.64	0.80	0.60

Legend
Very Good
Good
Satisfactory
Unsatisfactory

4.2.3. Sensitivity Analysis

Each parameter was separately varied, in increments of 10%, from -30% up to +30%, in order to evaluate the sensitivity of eleven SMA parameters. Each of the parameters was changed while holding the rest of the parameters the same. Percentage of dissimilarity in the simulated volume and peak were then plotted against the percentage of variation of each parameter, as shown in Figures 4-9 and 4-10.

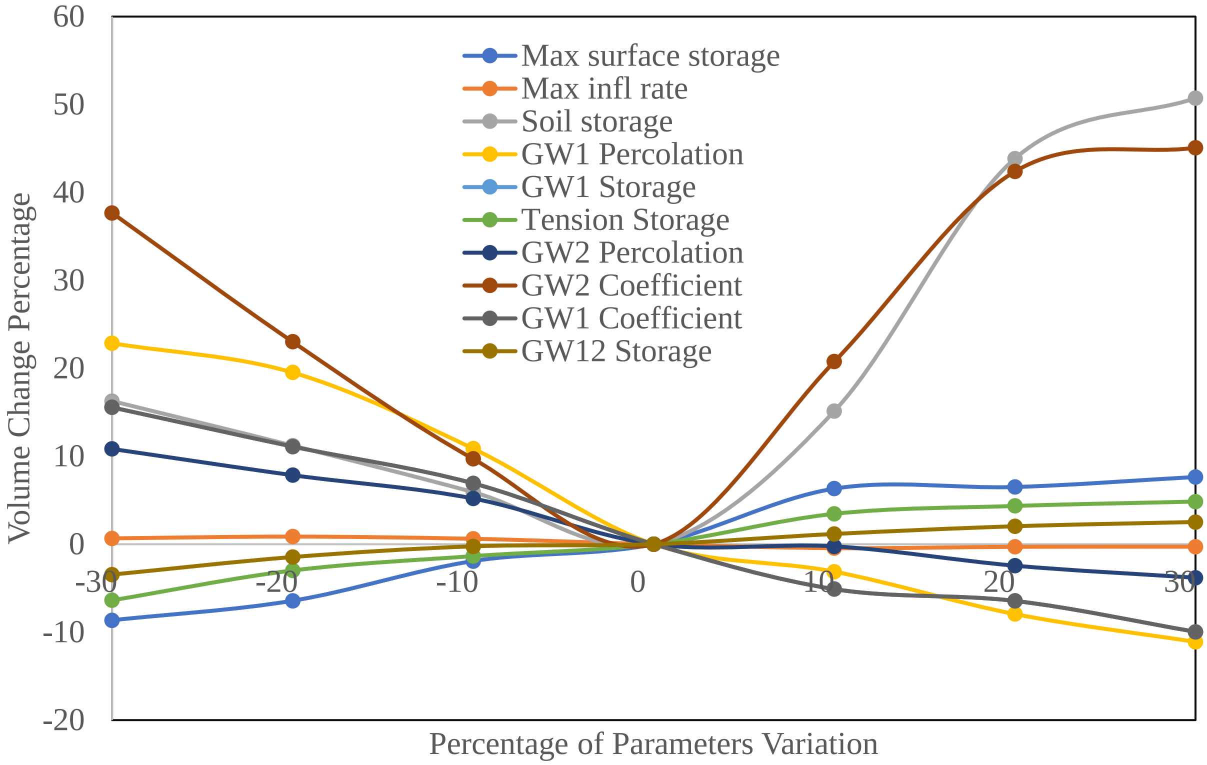

Figure 4-9: Percentage changes in simulated volume plotted against the percentage variation of each parameter.

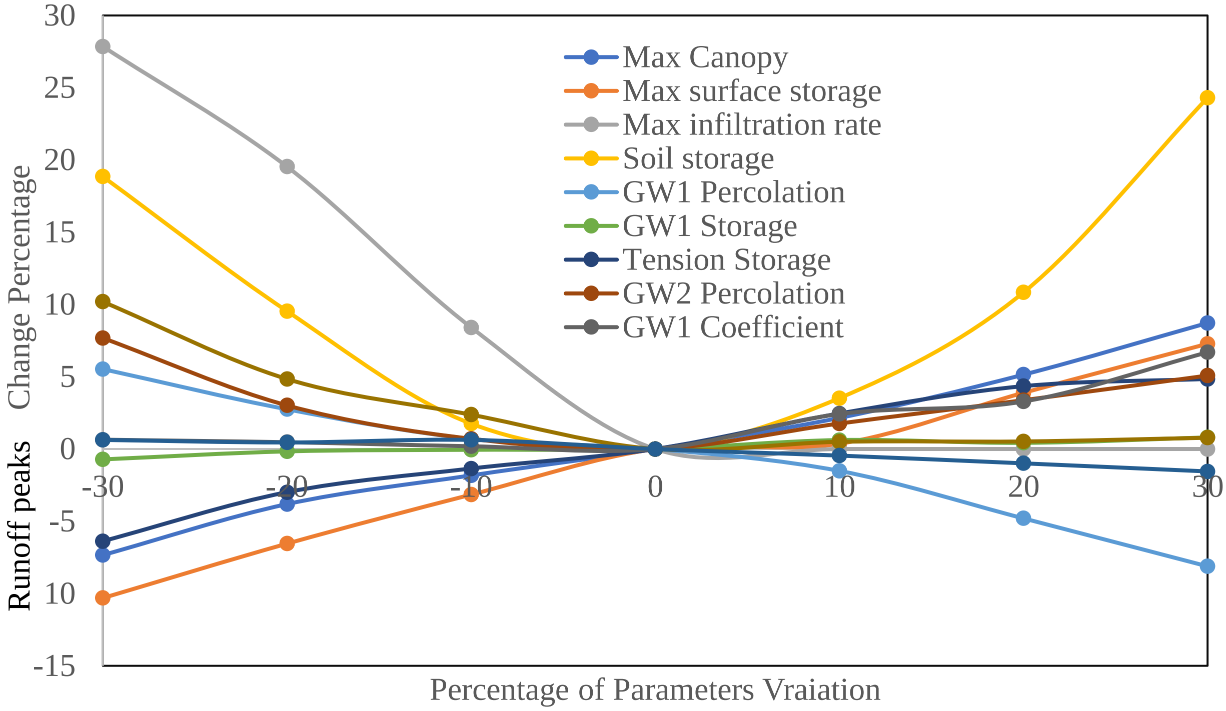

Figure 4-10: Percentage changes in simulated peak plotted against the percentage variation of each parameter.

The elasticity of the different parameters was evaluated, and then the parameters ranked from the one that is most sensitive to the one that has least sensitivity. This was important in order to find out how sensitive the computed runoff and computed peak are.

Table 4-6: SMA parameters sensitivity ranking for runoff volume

Rank	Parameter	Average Elasticity Ratio
1	Soil storage (mm)	0.62
2	Max Canopy (mm)	0.49
3	GW2 Coefficient (h)	0.39
4	GW1 Percolation (mm/h)	0.29
5	GW2 Percolation	0.17
6	GW1 Storage (mm)	0.11
7	GW1 Coefficient (h)	0.11
8	Max surface storage (mm)	0.10
9	Tension Storage (mm)	0.05
10	GW2 Storage (mm)	0.03
11	Max infiltration rate (mm/h)	0.02

It was established that the runoff volume was more sensitive to the soil storage, Maximum Canopy and GW2 coefficient as shown in Table 4-6. Similarly, it was established that the peak discharge was more sensitive to soil storage, maximum infiltration and maximum surface storage and GW1 percolation rate respectively. This is as shown in Table 4-7.

Table 4-7: SMA parameters sensitivity ranking for runoff peaks

Rank	**Parameter**	**Average Elasticity Ratio**
1	Soil storage (mm)	0.50
2	Max infiltration rate (mm/h)	0.46
3	Max surface storage (mm)	0.24
4	Max Canopy Storage (mm)	0.23
5	Tension Storage (mm)	0.19
6	GW1 Percolation (mm/h)	0.18
7	GW2 Percolation (mm/h)	0.17
8	GW1 Coefficient (h)	0.15
9	GW2 Coefficient (h)	0.12
10	GW1 Storage (mm)	0.04
11	GW2 Storage (mm)	0.02

4.2.4. Generated Discharge

Validated model was used to generate streamflow data for the period 2000 – 2019 (Figure 4-11).

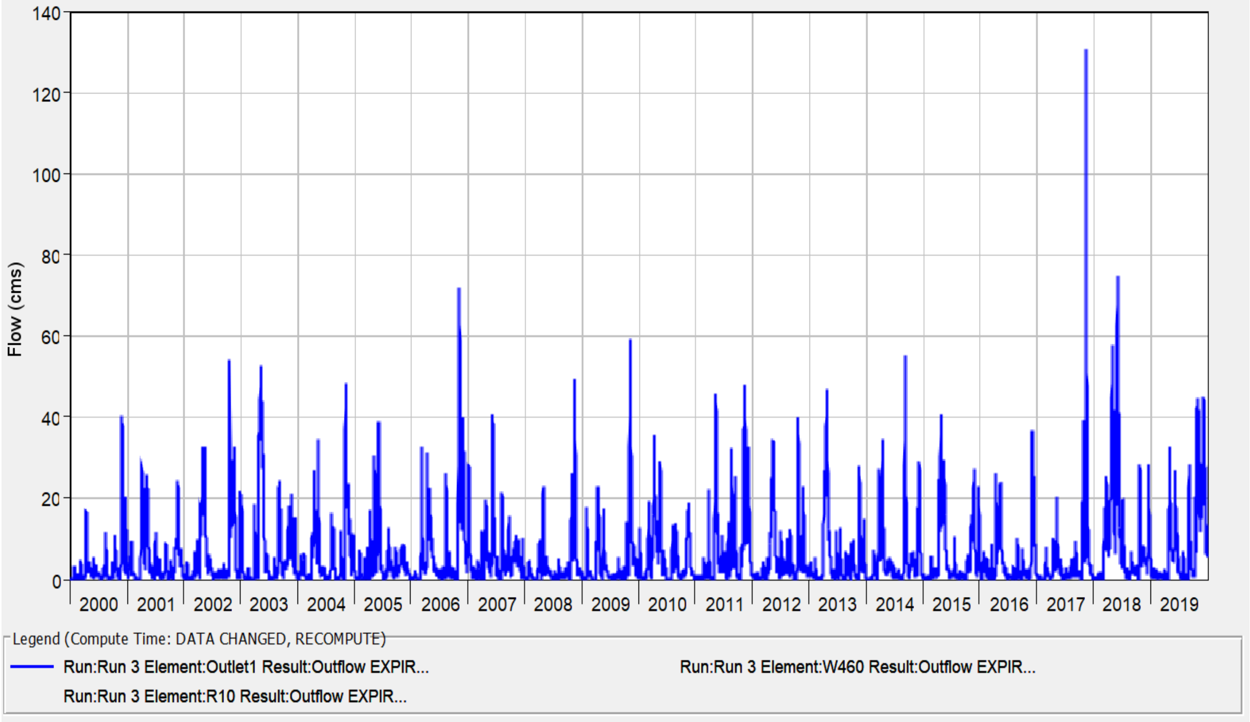

Figure 4-11: Stream flow at the catchment outlet

4.2.5. Discussion

HEC-HMS model required proper calibration using parameters before application in the Nanyuki catchment for correct prediction of runoff. The parameters required for the calibration are mostly related to the properties of the soil. For a given level of accuracy, these parameters need careful observation and some site investigations. For this study, the criteria for the Nanyuki catchment were gathered from secondary sources such as literature. This is because there were no records and neither were any site investigations carried out for the study. The results obtained with this form of data estimation are extremely satisfying. FAO CLIMWAT data was used to estimate evapotranspiration which is a vital input data for continuous modeling. In general, the percentage error in volume varies between 0.87% and 19.64%. The percentage error in peaks range from 0% to 54.4%, an illustration of a very good and satisfactory model performance. The Nash-Sutcliffe efficiencies varies between 0.47 and 0.88, an indication of satisfactory and very good model performance. The coefficient of correlation R^2 ranges from 0.72 to 0.94, which, according to Table 4-5, indicates a good to very good performance. However, 2006 and 2007 exhibit very low model efficiencies and low correlation between observed and simulated. On model sensitivity, storage parameters and the rate of infiltration have been found to be highly sensitive parameters.

4.3. Impact of Reservoirs on Downstream Flows

4.3.1. Water Demand/Abstraction Vs Observed Discharge

Water abstraction from Nanyuki River mainly supports domestic and agricultural demand sectors including watering construction sites to reduce dust pollution. The highest abstractor has a permit of 961.92 m^3/day while the lowest has a permit of 2 m^3/day. Total abstraction as per the data provided is approximately 3500 m^3/day translating to approximately 1 m^3/s. Figure 4-12 shows the mean monthly discharge (2000 – 2007) at gauging station 5B20.

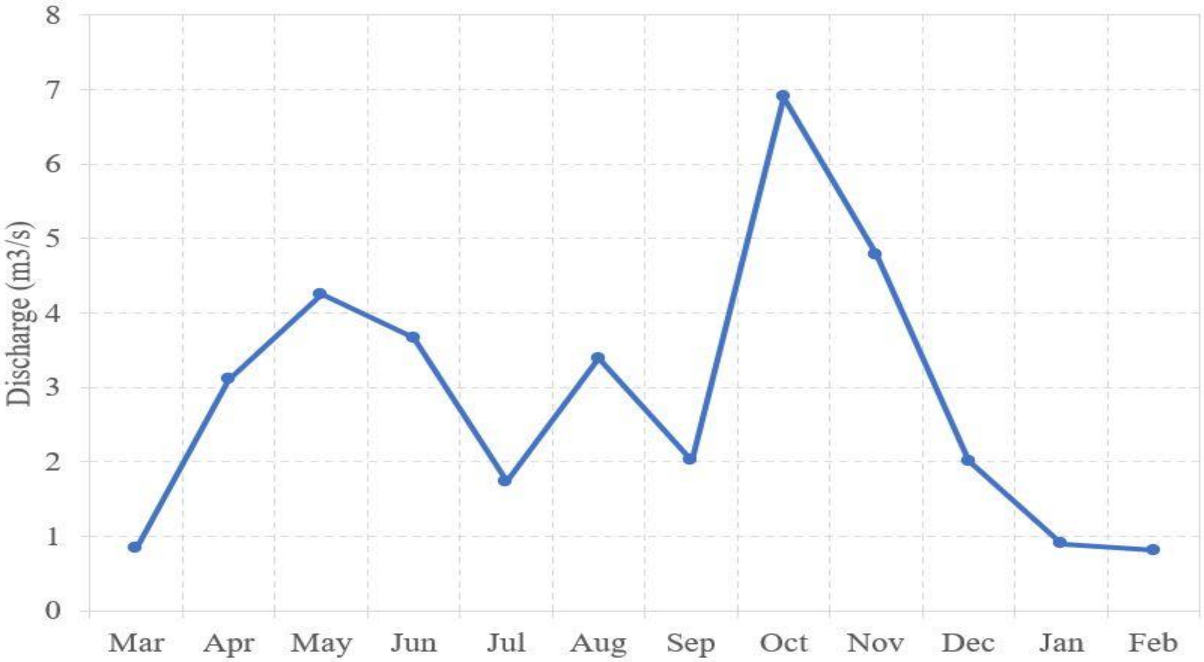

Figure 4-12: Mean Monthly flow at gauging station RGS 5B20 (2000 – 2007)

The highest mean monthly discharge record in the seven months is approximately 7 m^3/s while the lowest is less than 1 m^3/s. The lowest discharge record occurs between the months of January and March. The permitted abstraction volume is higher than the flows in River Nanyuki during the critical times indicating that at times, the river completely(ŞEN & AL-SUBA'I, 2002)(<*Ajayi et al.pdf*>, n.d.) dries-up particularly when the flows are below 1 m^3/s.

Table 4-8 illustrates the number of abstraction locations with reference to the system type including the volume of water abstracted in the selected river systems in the study area (Liniger, Wiesmann, et al., 2005). A steady increase in the number of portable pumps can be observed over the period across the three river systems.

Table 4-8: Number of abstraction locations in the selected river systems

Type of Abstraction	Likii		Burguret		Nanyuki	
	1997	2002/4	1997	2002/4	1997	2002/4
Fixed pump	1	4		5	10	22
Furrow	2	1	5	2	2	6
Furrow to pipe		1				
Gravity pipe	3	11	2	4	5	12
Hydram		2		3		
Portable pump	9	19	36	100	17	33
Total No. of Abstraction Points	15	38	43	113	34	73
Total abstraction amount in l/s	43	343	113	240	123	197

Source: (Liniger, Wiesmann, et al., 2005)

It is noted that portable pumps for the period (1997 – 2004) accounted for 2–22% of the gross abstractions for the three rivers. Piped gravity conveyance systems that were noted to be predominant in most community water supply projects, accounted for 30–70% of total water abstractions in the dry season. A key observation worth noting is that over the 7-year period of consideration, water abstraction from the three river systems increased drastically. In all the cases, the number of abstractors for the river systems presented doubled. Aeschbacher et al., 2005; Wiesmann et al., 2000 noted that the rapid-growing river water abstractions partly contributed to reduction in the low flows; Q80 and Q95. Most of the abstractions in the Nanyuki Catchment is mainly for irrigation purposes and thus highest abstractions occur during the dry periods, when flows in the river are low. Figure 4-13 indicates the low flows Q80 and Q95 for the periods 1971-1980, 1981-1990, and 1991-2000. The observation conforms to earlier results by (Liniger, Gikonyo, et al., 2005) on the decreasing flows over time due to constant increase in abstractions. The Q80 reduced from the 1970s to the 1990s to about half while the Q95 flow declined to a quarter and less. Decadal Mean Annual Precipitation for the period 1971-1980, 1981-1990, 1991-2000, and 2000-2001 (Figure 4-14) indicates no decreasing trend and thus climate change may not be the cause of the fast-decreasing low flows. As river water abstractions increases, the limited water resources become even more scarcer and thus results to constant conflicts between different demand sectors over available water resources.

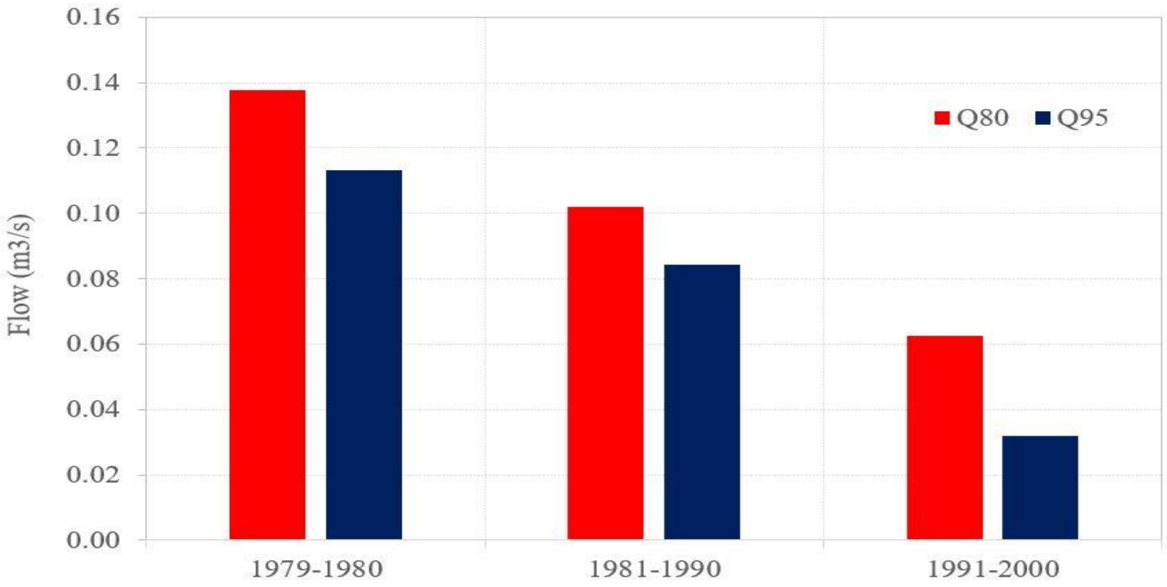

Figure 4-13: Low flows Q80 and Q95 for the periods 1971-1980, 1981-1990, and 1991-2000.

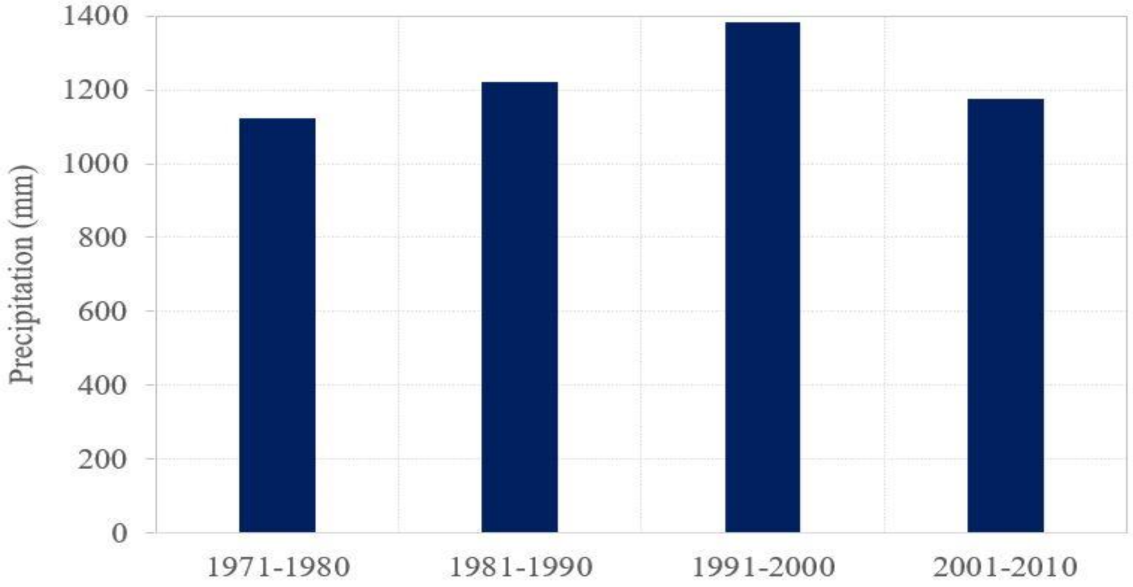

Figure 4-14: Decadal Mean Annual Precipitation for the period 1971-1980, 1981-1990, 1991-2000, and 2000-2001.

4.3.2. Impact of Dams to Downstream Flow

Overall, any kind of abstraction will always reduce the flow profile both in the dry and wet season. Depending on the purpose of abstraction, irrigation/agricultural, industrial, water supply for domestic use etc., the peak flood will always be affected at different magnitudes. For instance, irrigation/agricultural demand may not affect peak floods since no irrigation happen in the rain season when we expect a build-up of flows due to increased surface runoff. However, other forms of demands will require constant supply throughout and thus will reduce both the peak floods and low flows. This is the similar scenario assumed in this research resulting to a uniform decrease in flow magnitude between the head flow and flows after the abstraction location. Figures 4-15, 4-16 and 4-17 indicates monthly average instream flow requirement delivered to the downstream for the two scenarios. Flows downstream of the dams differs marginally for the pre-dam conditions and post-abstraction state as storage enhances flows downstream. No abstraction was implemented beyond the assumed location of abstraction which is just upstream of reservoir 2. However, a variation in the flow can still be observed in the pre- and post-dam flow condition.

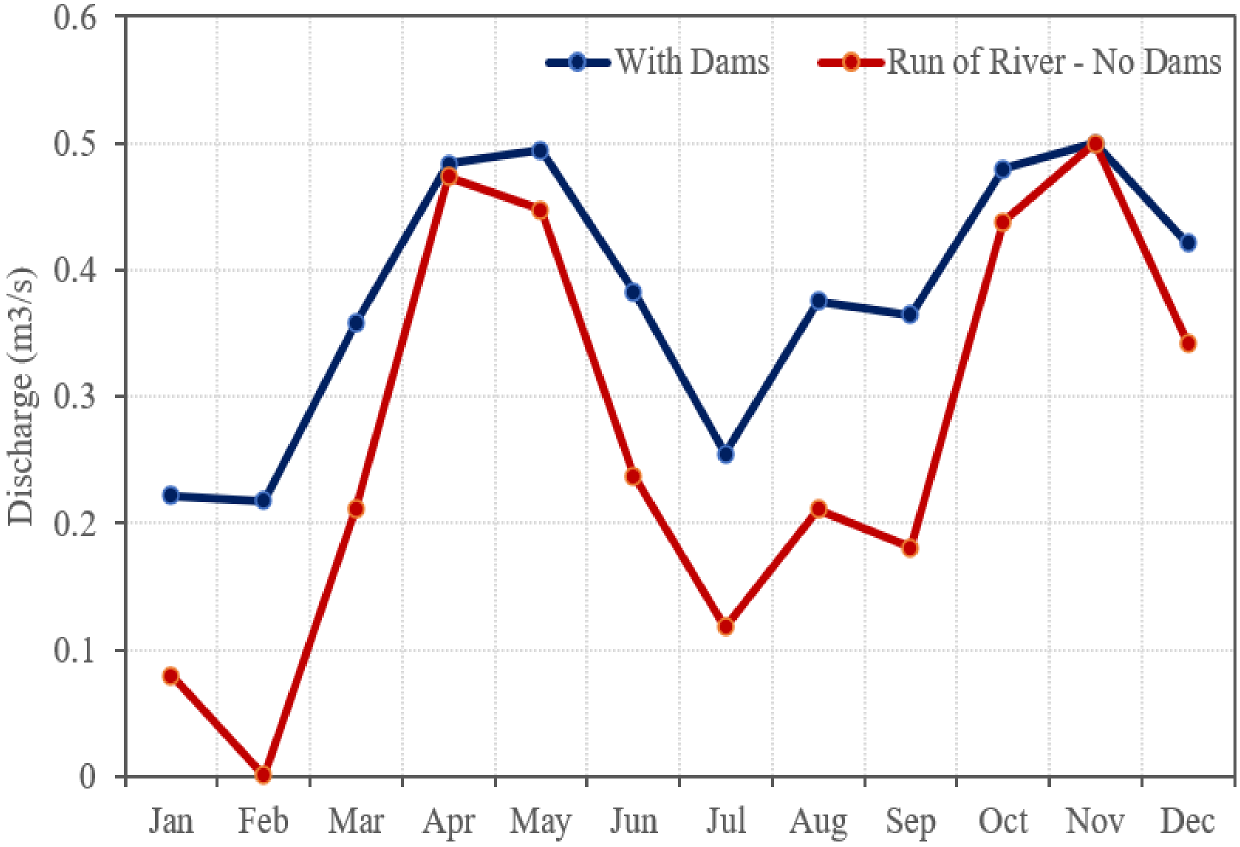

Figure 4-15: Instream flow requirement delivered for 6.0 m^3/s as abstraction

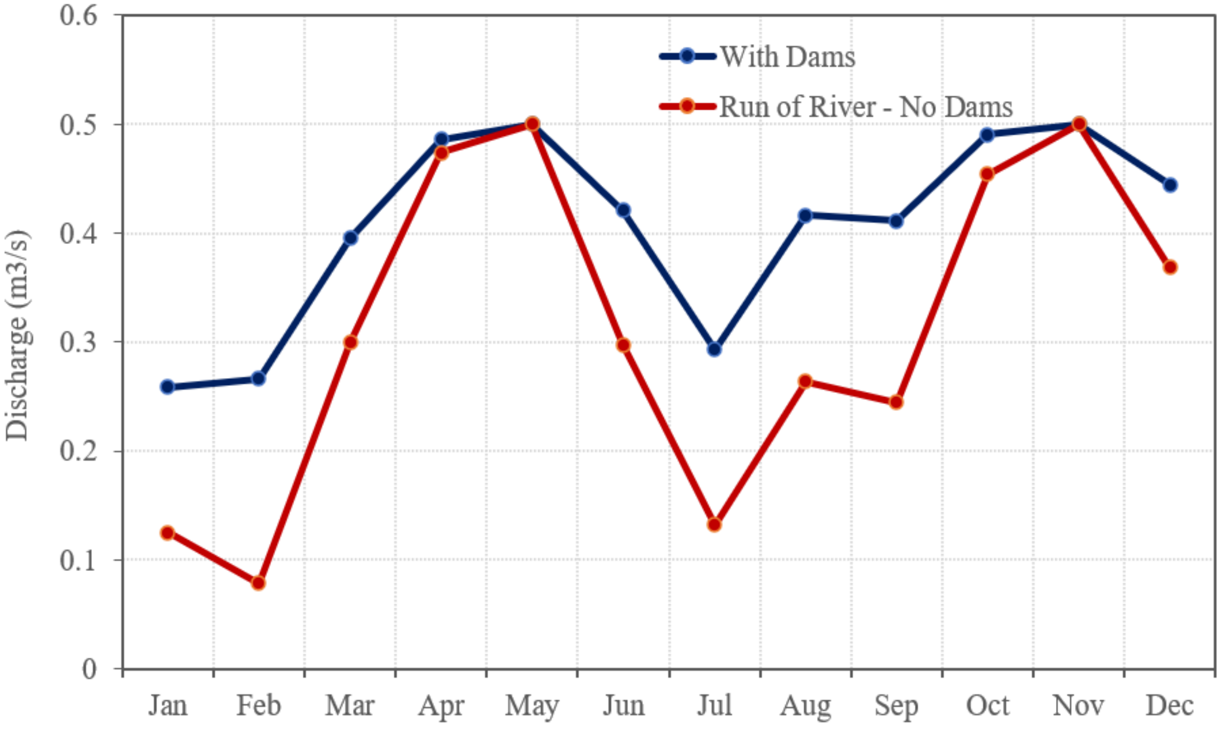

Figure 4-16: Instream flow requirement delivered for 4.5 m^3/s as abstraction

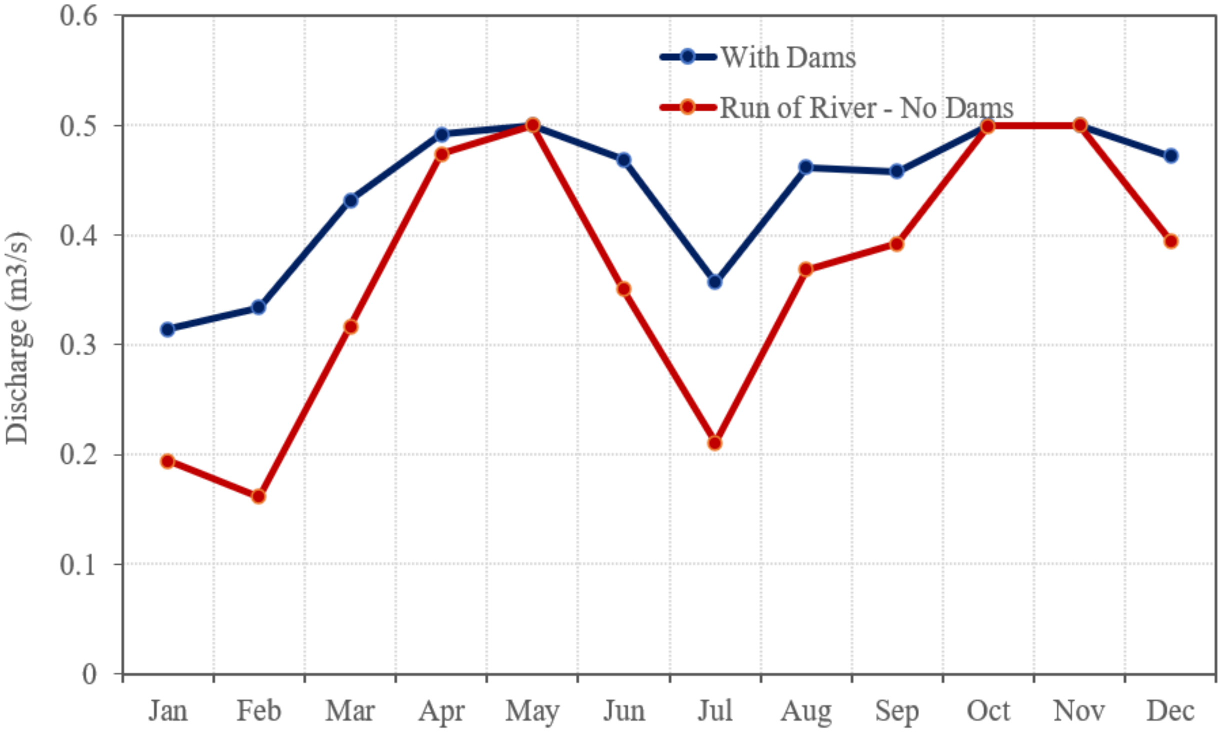

Figure 4-17: Instream flow requirement delivered for 3 m^3/s as abstraction

Figure 4-18 illustrates the combine monthly variations in the storage volumes for the two reservoirs. Dam 1 and 2 shows a variation in storage due to an operational rule to release a fixed water volume especially during the dry month's period as instream water requirement. The results from WEAP simulations illustrate that reservoirs irrespective of size will alter flow regimes. Storage decreases during January, February, and March. Dam will definitely influence elements of the riverine ecosystem that are dependent on the occurrence of peak floods. (Ngigi et al., 2008) noted that such reduction in river flows is not as significant as the over-abstractions that ensue during the dry-period with no storage conditions. In a nutshell, reduction in flood peaks is inconsequential when critically compared to the decrease in dry season flows. Therefore, an increase in the low flows resulting from flood storage implies that more water available for downstream water users. This is critical in watersheds such the Nanyuki for which drastic increase in abstraction decreases downstream flows. Flood storage and release during low flow will definitely address conflicts between the pastoralists migrating to the upstream of the river as flows decreases as a consequence of a high level of water abstractions and the upstream water uses for irrigation and other water uses. Permits for irrigation should state that water should be abstracted for agriculture only during the dry period to prevent further reduction in flood peaks.

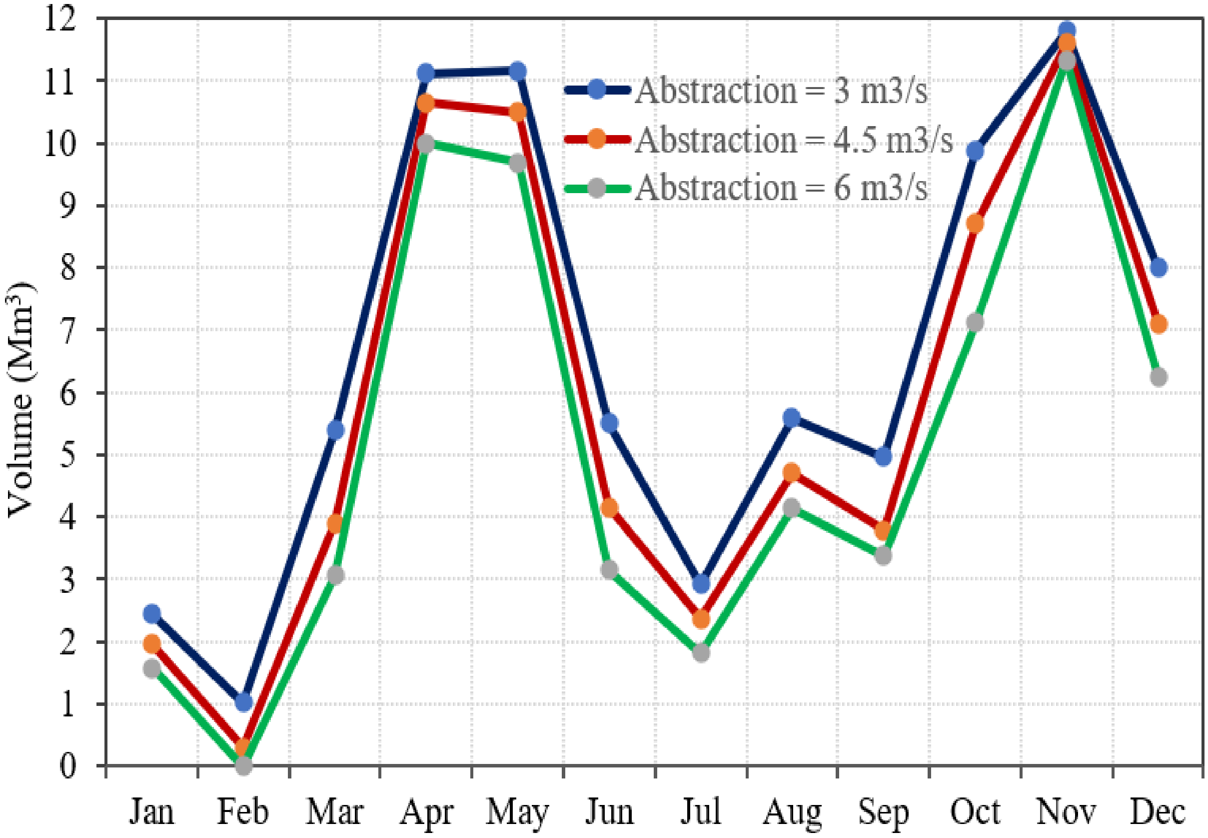

Figure 4-18: Variation in monthly reservoir storage with the implementation of a fixed release operational rule

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

Identification of probable dam locations is a critical strategy in water resources management especially in highland-lowland systems such as the Ewaso Ng'iro River Basin. For dam siting along the Nanyuki River, GIS and MCDA methods with an overlay of thematic features where integrated into this study. Elevation, slope, curve number, lithology, land use/landcover, and stream order (Strahler Classification) were the six thematic attributes taken into account. Two appropriate locations were sited downstream of the catchment at location 0^o 12' 35.5''N, 37^o 0' 29''E and 0^o 15' 45''N, 36^o 57'0.95''E for dam 1 and 2 respectively. The elevation of the dam axis for Dam 1 is 1750 meters (dam width: 460 meters), and that of Dam 2 is roughly 1694 meters (width of 600 m). For Dams 1 and 2, the predicted water storage volumes are 5.8 and 6.1 Mm^3, respectively. Since Dam 1's top water level is 1762 meters above sea level, its height is 12 meters. At an elevation of 1708 meters, Dam 2's height is 14 meters high. The outcomes show the potential of GIS and RS as a rapid and inexpensive method for selecting appropriate dam locations. It is crucial to remember that the approaches should be combined with more conventional techniques in order to confirm and validate the selected sites. Modern water resource management relies heavily on geospatial data. For reservoir development, the AVE curve is a vital decision-making tool.

1. The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) was adopted for simulating river discharge at the identified dam locations along the river reaches. Model output was matched with observed discharge data to establish the suitability of model in predicting streamflow. Model calibration was performed using a daily time step flow data from 2001 to 2005. The model was further then, validated using data for the period between 2006 and 2007. We evaluated model performance based on statistically computed parameters in addition to the visual inspection and comparison of the resultant hydrographs. The coefficient of determination (R^2), Root Mean Square (RMS), Nash-Sutcliffe (NSE) for the calibration period were 0.86, 0.4, and 0.85 respectively, an indication of a very good model performance. Similarly, R^2, RMS, and NSE for the validation period were 0.80, 0.6 and 0.64 respectively an affirmation of the performance achieved at the calibration period. In general, the performance statistics illustrates that HMS Model gives a good stream prediction for the Nanyuki River. A further understanding of the interrelationship between different key parameters was enhanced through sensitivity analysis. It was established that the runoff volume was highly sensitive to soil storage, Maximum Canopy and GW2 coefficient. Similarly, it was established that the peak discharge was more sensitive to soil storage, maximum infiltration and maximum surface storage and GW1 percolation rate respectively. Similar modelling studies were carried out on the Naro Moru river, a tributary of the Ewaso Ng'iro river using the Soil Water Assessment Tool (SWAT). The model satisfactorily predicted stream flow in the Naro Moru catchment in the Ewaso Ng'iro River Basin.

2. Water abstraction from Nanyuki River mainly supports domestic and agricultural demand sectors including watering construction sites to reduce dust pollution. Decadal Mean Annual Precipitation for the period 1971-1980, 1981-1990, 1991-2000, and 2000-2001 indicates no decreasing trend and thus climate change may not be the cause of the fast-decreasing low flows. As river water abstractions increases, the limited water resources become even more scarcer and thus results to constant conflicts between different demand sectors over available water resources. Most of the abstractions in the catchment is mainly for irrigation purposes and thus highest abstractions happen during the dry periods, when flows in the river are low.

3. Reservoirs irrespective of size will alter flow regimes and increase flow volumes in the river during the dry spell. Although, the benefits of water storage for the case of Ewaso Ng'iro may outweigh the negative impacts, there must be a limit beyond which such impoundment may have adverse impacts to the ecosystem functioning resulting to a shift in the balance.

5.2. Recommendations

1. The selection of the potential dam site considered all parameters available. However, factors such as economic performance and proximity to the users among others that have a socio-economic impact on the site suitability have not been taken into account. This implies that the GIS techniques coupled with remote sensing should be used together with other traditional methodologies to ascertain accurate dam site. Future research on the subject can also consider DEM with finer resolution, including – aerial and satellite - in combination with deep and machine learning to improve on the accuracy in site selection.

2. Although dams are recommended for a case of Nanyuki River, excessive impoundment may limit flood water discharges to the downstream and thus depriving vital ecosystem services that are depended on the flood water. Therefore, it is necessary to establish the safe extent of impoundment which can ensure a balance between prevention of conflicts amongst users and sustaining peak floods dependent ecosystem.

3. Calibration of a hydrologic model is a primary step in towards development of an accurate and reliable model. To make the model more robust under a variety of conditions, model parameters are required to be refined through adoption of historical storms. Data collected must be checked carefully for correctness considering the local condition to ensure accuracy of the calibrated and validated model.

4. Traditionally river discharge from high humid elevation provides a secure surface water to sustains forage production downstream and vital dependent ecosystems. An example of such vital ecosystem in the Ewaso Ng'iro watershed is the Lorian swamp in the lowlands. Flood water in the rainy seasons is discharged in the swamp which has a myriad of ecosystem services

including recharge of the Merti Aquifer, a key fresh groundwater source for both Kenya and Somalia. It is recommended that a study be undertaken to establish any potential impact of the proposed dams to the swamp and ultimately recharge into the important fresh-groundwater storage in the Lorain Swamp.

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ANNEXES

Annex 4.1: Mean Monthly Rainfall (2000 – 2019)

Annex 4.2: Mean Monthly Discharge (2000 – 2007)

Annex 4.1: Mean Monthly Rainfall (2000 – 2019)

Gauge 1

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	16.47	7.56	18.46	51.34	50.49	26.54	23.82	55.58	16.17	55.08	119.49	37.49
2001	63.55	8.94	99.06	159.63	48.45	47.66	29.66	63.46	23.47	68.24	153.76	29.35
2002	21.23	9.54	71.69	157.32	135.62	31.68	23.09	38.87	23.18	90.54	112.98	92.5
2003	16.08	12.54	49.42	191.87	147.4	18.99	33.69	109.73	19.93	107.77	96.62	41.24
2004	53.9	19.24	46.74	125.9	108.93	29.67	60.87	62.95	56.18	104.6	151.16	49.55
2005	24.62	18.66	35.93	128.6	138.87	29.23	56.54	40.21	59.55	70.25	55.15	23.01
2006	17.37	20.45	58.98	143.66	56.17	27.4	28.86	92.99	27.23	112.24	189.63	99.9
2007	32.58	29.28	28.63	110.87	76.92	97	71.83	72.73	76.16	85.95	75.74	30.23
2008	37.63	10.5	62.77	73.04	34.99	18.83	30.63	26.5	39.47	115.76	137.69	28.68
2009	36.62	17.53	24.72	79.3	61.38	22.57	15.73	29.7	16.06	111.24	76.94	71.52
2010	32.29	76.72	127.7	142.4	119.57	24.09	49.46	104.49	20.89	72.36	74.18	20.54
2011	12.95	17.53	58.27	79.25	68.7	58.15	87.47	114.77	42.6	130.73	224.62	58.18
2012	10.57	14.11	15.08	162.6	147.15	55.4	71.4	77.66	33.42	95.02	61.25	50.25
2013	32.38	6.56	73.48	227.09	60.84	38.94	50.93	55.82	45.26	59.27	135.3	47.35
2014	9.55	41.65	68.62	96.54	49.07	25.74	23.48	99.23	40.08	84.26	117.37	43.23
2015	14.07	24	27.92	198.59	63.31	16.23	22.37	22.42	10.66	97.94	149.97	85.58
2016	49.04	17.33	29.27	146.91	82.32	24.14	17.33	39.3	15.93	31.94	109.28	26.1
2017	10.32	31.85	14.54	64.05	88.47	17.12	49.1	61.26	24.33	123.42	174.05	18.17
2018	9.58	7.04	138.09	264.72	152.35	187.37	29.6	38.19	33.33	61.84	95.75	106.69
2019	31.11	16.08	16.4	95.76	83.99	102.53	26	53.69	57.59	177.04	250.48	119.74

Gauge station location is at the centre of each sub-basin.

Gauge 2

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	15.7	8.16	18.81	50.64	41.89	21.09	20.82	49.5	18.22	48.14	115.47	36.82
2001	54.08	10.07	86.52	141.85	43.25	43.21	26.59	54.29	25.61	58.25	141.52	29.18
2002	19.33	10.57	61.58	158.11	119.05	28.63	20.57	34.32	30.9	89.45	104.55	88.22
2003	14.84	12.54	52.39	179.76	122.91	16.06	26.18	107.66	24.89	96.79	98.36	45
2004	43.89	20.56	43.48	124.46	87.77	25.89	49.4	47.13	44.93	88.67	141.27	50.42
2005	23.6	17.08	34.34	129.36	123.4	26.59	45.99	36.41	69.1	60.15	59.18	24.09
2006	16.12	20.48	54.3	142.74	52.35	23.03	22.9	81.9	31.67	103.27	185.44	95.89
2007	29.69	24.11	32.64	104.87	68.24	80.22	62.9	58.76	79.14	79.8	77.77	30.74
2008	35.33	9.44	63.96	63.48	32.37	16.92	28.59	24.17	45.41	97.8	111.68	27.64
2009	33.55	17.38	26.46	78.78	57.88	20	13.42	27.26	18.42	97.18	74.66	69.42
2010	27.2	72.84	108.64	134.96	95.51	21.59	44.13	84.83	20.62	62.48	83.41	20.95
2011	12.29	16.9	55.42	75.42	63.06	55.49	71.3	101.66	48.02	116.15	193.35	53.09
2012	9.7	14.19	15.8	150.32	117.56	49.64	53.92	67.14	36.54	77.18	56.89	42.13
2013	23.67	6.5	65.65	201.29	50.37	37.65	40.94	47.9	45.16	41.99	103.99	37.14
2014	8.07	37.9	66.15	87.68	44.61	25.95	20.95	96.69	39.82	63.76	98.72	41.19
2015	12.09	19.44	31.27	178.07	51.1	16.09	22.04	21.36	12.2	70.25	130.08	78.87
2016	36.5	15.33	30.08	129.86	63.94	22.44	16.31	34.98	19.49	24.36	100.64	25.38
2017	8.74	24.02	16.81	56.19	80.24	17.67	40.69	52.93	30.96	87.25	138.54	15.71
2018	7.96	7.07	140.49	252.5	128.14	170.48	30.34	36.45	39.35	46.84	85.52	102.31
2019	25.99	14.09	17.68	80.99	74.47	103.95	27.96	45.29	60.13	133.92	230.14	104.8

Gauge 3

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	18.96	12.3	26.6	58.11	43.23	17.32	19.39	44.35	16.01	55.21	148.79	44.18
2001	66.36	15.24	129.93	148.47	47.87	41.08	28.31	54.22	22.63	62.63	181.97	34.37
2002	20.78	17.16	100.38	179.92	130.72	24.18	20.07	28.78	27.59	100.29	130.5	108.68
2003	17.29	19.44	83.91	201.14	144.9	15.69	26.71	108.37	22.9	108.42	127.79	55.34
2004	55.61	31.9	73.92	139.43	113.35	24.06	51.3	41.8	38.14	103.05	173.5	69.32
2005	35.51	25.63	53.99	153.02	146.17	23.57	47.55	37.27	60.21	75.94	80.31	27.68
2006	19.92	34.31	79.22	161.88	65.54	22.11	20.98	86.36	27.76	117.39	235.08	117.22
2007	34.36	31.98	61.61	125.08	76.83	77.6	62	53.67	64.43	90.63	99.3	37.63
2008	42.34	12.84	89.93	69.78	33.03	15.74	25.27	22.81	37.7	115.7	142.82	31.5
2009	47.59	22.3	39.3	81.94	70.69	17.46	14.84	23.55	16.82	112.94	92.41	78.64
2010	31.92	99.52	182.23	155.5	101.69	19.61	39.78	75.45	17.59	69.93	109.56	24.33
2011	14.86	27.94	90.31	86.98	74.61	56.35	71.53	89.94	44.07	133.04	262.76	63.79
2012	10.72	22.14	25.03	164.01	133.53	45.58	52.75	61.47	32.51	93.31	77.08	42.77
2013	24.15	9.36	93.16	218.18	45.02	30.86	36.67	40.76	34.2	41.89	131.2	45.48
2014	8.72	59.05	99.65	93.75	44.96	21.35	20.84	89.54	27.07	66	113.76	43.99
2015	13.27	27.11	45.35	197.38	52.37	12.4	21.16	18.45	9.21	78.54	158.85	92.52
2016	38.69	22.97	43.35	138.42	65.36	18.5	13.53	31.64	13.83	25.31	124	28.56
2017	9.4	40.77	24.68	43.65	73.93	11.58	33.62	43.72	23.89	85.02	152.32	17.71
2018	8.57	9.71	223.63	269.62	143.96	162.97	27.78	32.4	30.66	51.21	97.26	117.71
2019	31.99	20.72	25.25	94.19	75.23	98.44	24.77	44.59	49.03	172.78	279.09	125.94

Gauge 4

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	15.69	8.55	17.83	54.9	45.41	21.98	21.43	52.3	20.12	50.09	103.48	36.2
2001	55.42	11.01	85.34	142.67	43.83	47.55	28.16	54.67	30.79	57.55	122.23	26.57
2002	19.92	11.23	58.05	156.46	115.74	33.14	21.54	39.42	34.05	99.2	90.76	88.64
2003	14.97	13.05	45.48	183.09	121.94	19.92	26.76	122.3	26.49	104.06	88.14	41.97
2004	43.88	21.42	38.4	128.51	91.6	28.8	55.23	52.34	47.68	82.37	135.61	45.51
2005	21.83	17.22	31.16	125.83	121.29	29.91	43.68	38.67	74.63	60.85	51.07	20.67
2006	15.75	20.1	51.35	153.49	55.96	22.67	24.21	84.19	35.66	105.32	171.6	88.4
2007	29.86	25.07	30.25	106.29	80.92	83.05	67.3	69.21	88.5	83.35	68.87	26.96
2008	35.31	10.55	62.22	60.58	34.46	19.05	27.82	27.06	63.74	103.48	101.17	25.21
2009	32.2	17.88	24.25	81.51	56.44	23.12	13.88	31.54	20.06	101.43	64.78	56.17
2010	28.37	74.18	103.24	129.57	93.93	28.63	48.12	94.79	24.66	59.19	76.27	19.11
2011	12.36	17.56	51.37	83.08	63.08	65.55	63.41	122.8	53.9	117.18	172.24	49.8
2012	10.06	14.05	14.22	165.15	131.26	53.08	58.96	76.9	38.83	79.92	55.47	39.87
2013	25.49	6.65	68.24	199.14	60.39	48.57	43.97	63.06	58.52	43.09	87.62	39.85
2014	8.55	39.68	68.76	92.24	50.24	32.92	24.45	120.84	36.04	67.79	91.32	38.23
2015	12.78	20.55	31.23	186.63	59.56	23.44	25.28	26.3	14.45	81.12	110.38	70.09
2016	44.44	15.82	28.47	141.24	77.83	27.66	19.89	43.38	24.54	26.7	105.82	24.69
2017	9.28	28.91	17.52	63.82	92.82	20.24	36.03	67.98	34.97	100.97	125.14	14.35
2018	8.42	7.62	127.15	261.63	149.17	186.07	38.05	38.64	46.79	55.9	80.02	94.18
2019	27.6	12.93	18.33	87.56	86.35	110.77	35.1	51.69	56.73	154.13	199.93	95.2

Gauge 5

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	15.69	8.55	17.83	54.9	45.41	21.98	21.43	52.3	20.12	50.09	103.48	36.2
2001	55.42	11.01	85.34	142.67	43.83	47.55	28.16	54.67	30.79	57.55	122.23	26.57
2002	19.92	11.23	58.05	156.46	115.74	33.14	21.54	39.42	34.05	99.2	90.76	88.64
2003	14.97	13.05	45.48	183.09	121.94	19.92	26.76	122.3	26.49	104.06	88.14	41.97
2004	43.88	21.42	38.4	128.51	91.6	28.8	55.23	52.34	47.68	82.37	135.61	45.51
2005	21.83	17.22	31.16	125.83	121.29	29.91	43.68	38.67	74.63	60.85	51.07	20.67
2006	15.75	20.1	51.35	153.49	55.96	22.67	24.21	84.19	35.66	105.32	171.6	88.4
2007	29.86	25.07	30.25	106.29	80.92	83.05	67.3	69.21	88.5	83.35	68.87	26.96
2008	35.31	10.55	62.22	60.58	34.46	19.05	27.82	27.06	63.74	103.48	101.17	25.21
2009	32.2	17.88	24.25	81.51	56.44	23.12	13.88	31.54	20.06	101.43	64.78	56.17
2010	28.37	74.18	103.24	129.57	93.93	28.63	48.12	94.79	24.66	59.19	76.27	19.11
2011	12.36	17.56	51.37	83.08	63.08	65.55	63.41	122.8	53.9	117.18	172.24	49.8
2012	10.06	14.05	14.22	165.15	131.26	53.08	58.96	76.9	38.83	79.92	55.47	39.87
2013	25.49	6.65	68.24	199.14	60.39	48.57	43.97	63.06	58.52	43.09	87.62	39.85
2014	8.55	39.68	68.76	92.24	50.24	32.92	24.45	120.84	36.04	67.79	91.32	38.23
2015	12.78	20.55	31.23	186.63	59.56	23.44	25.28	26.3	14.45	81.12	110.38	70.09
2016	44.44	15.82	28.47	141.24	77.83	27.66	19.89	43.38	24.54	26.7	105.82	24.69
2017	9.28	28.91	17.52	63.82	92.82	20.24	36.03	67.98	34.97	100.97	125.14	14.35
2018	8.42	7.62	127.15	261.63	149.17	186.07	38.05	38.64	46.79	55.9	80.02	94.18
2019	27.6	12.93	18.33	87.56	86.35	110.77	35.1	51.69	56.73	154.13	199.93	95.2

Gauge 6

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	32.02	17.87	37.31	140.7	88.65	44.45	47.75	70.04	38.11	116.94	214.01	67.89
2001	118.15	22.35	133.66	220.82	106.1	83.99	66.4	74.07	47.26	98.92	240	47.19
2002	33.85	26.15	82.26	293.78	237.13	45.12	47.09	57.87	73.96	262.98	194.74	138.66
2003	27.84	30.85	85.24	376.28	279.11	38.8	56.95	128.96	58.73	232.92	183.49	72.72
2004	58.88	50.14	81.37	211.44	164.82	60.03	97.5	75.44	71.41	151.72	221.36	71.93
2005	40.51	23.97	50.55	220.38	259.11	57.52	95.18	91.65	78.53	162.16	120.1	28.06
2006	32.36	38.28	106.76	275.21	175.42	42.81	45.24	143.75	70.94	259.32	340.48	165.04
2007	59.27	38.64	65.05	186.38	199.02	107.57	133.91	100.56	91.95	203.46	144.66	49.1
2008	60.35	21.02	100.71	135.79	83.86	38.43	60.18	48.59	85.47	217.59	171.05	36.56
2009	62.25	33.51	51.72	143.46	129.76	42.97	38.53	59.79	36.38	293.14	135.27	76.75
2010	50.05	145.63	156.36	227.03	205.62	40.44	101.9	112.54	37.71	140.19	164.39	36.48
2011	25.11	47.36	83.07	226.8	173.89	85.17	140	153.94	110.85	264.67	329.5	71.85
2012	18.44	23.22	29.78	265.84	263.81	106.08	105.26	114.42	57.36	170.07	152.46	83.48
2013	46.25	14	97.61	369.94	74.9	73.95	76.26	88.12	64.27	84.3	182.98	56.1
2014	14.08	82.06	121.19	175.12	107.86	67.75	45.58	206.59	54.43	166.32	182.71	55.17
2015	22.17	35.74	54.84	370.4	132.68	32.39	59	46.08	24.78	168.29	245.64	107.08
2016	75.97	35.05	57.98	302.28	114.07	48.03	36.96	65.33	52.01	61.86	244.07	33.57
2017	14.87	59.22	34.35	103.1	133.8	33.03	56.59	96.59	53.25	233.66	239.74	26.52
2018	14.82	16.83	243.74	511.84	301.15	194.05	73.87	60	90.08	150.76	149.9	147.63
2019	49.54	28.78	34.38	179.98	176.21	164.19	53.66	96.54	80.35	377.6	361.05	147.33

Gauge 7

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	16.14	9.2	19.84	65.25	41.67	21.68	20.08	48.73	21.05	52.82	109.3	42.78
2001	63.4	12.56	93.73	131.84	39.59	43.57	30.62	44.64	33.89	55.9	132.25	31.03
2002	16.28	12.42	59.93	161.72	102.43	32.56	21.38	34.55	39.43	107.09	99.63	87.15
2003	14.89	14.21	49.11	194.43	122.22	20.41	28.46	106.07	27.77	114.78	92.19	48.74
2004	38.46	23.81	46.62	131.77	84.54	28.27	58.54	43.42	46.8	90.09	134.14	48.4
2005	20.17	17.88	34.01	128.55	121.16	25.56	42.56	37.4	78.72	70.5	53.26	23.79
2006	15.78	22.42	60.23	161.74	57.93	22.07	23.13	79.99	38.48	114.62	178.35	103.59
2007	29.49	25.58	33.41	109.19	89.54	73.08	65.71	52.1	84.05	91.73	70.85	28.14
2008	35.72	11.08	70.29	62.4	33.82	19.02	29.02	24.48	70.8	109.06	100.12	26.91
2009	32.74	18.85	27.11	78.14	50.27	22.88	15.18	30.49	21.09	114.65	62.94	69.83
2010	27.81	78.97	104.41	145.69	88.86	29.19	43.41	80.15	28.07	64.72	82.4	23.32
2011	13.13	21.02	51.56	97.35	60.5	60.63	67.61	97.77	60.68	131.54	190.12	50.46
2012	10.02	13.92	15.7	174.51	123.18	56.49	48.62	71.54	41.29	89.1	67.17	44.93
2013	29.54	7.71	80.53	226.48	65.02	49.66	47.53	56.39	54.98	47.3	99.59	45.53
2014	9.41	43.64	82.02	103.28	56.87	34.13	27.41	114.34	34.71	82.16	101.37	41.82
2015	14.18	22.7	37.28	216.49	64.86	21.08	27.53	25.48	18.08	91.29	126.43	81.3
2016	47.21	19.04	34.39	163.27	73.89	27.94	21.07	41.02	29.4	32.02	127	25.71
2017	10.24	33.28	21.65	66.53	82.23	20.34	34.32	62.09	36.91	115.35	143.38	17.07
2018	9.67	8.95	146.16	300.73	138.47	167.42	37.85	33.03	51.92	63.72	87.46	106.55
2019	30.77	14.35	21.89	93.02	110.18	105.63	34.28	52.81	57.21	187.02	209.69	107.01

Gauge 8

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	17.35	9.13	20.44	60.05	42.89	19.75	21.12	50.71	21.34	52.6	124.45	43.89
2001	65.74	11.77	90.17	142.78	42.95	40.5	30.95	49.64	31.18	56.02	150.57	32.73
2002	19.84	12.59	65.68	175.92	120.26	27.59	21.77	33.25	37.26	104.68	108.21	101.61
2003	16.02	14.33	52.8	202.6	134.72	17.69	26.16	106.45	29.96	110.16	105.52	52.93
2004	40.98	22.36	45.87	142.65	99.28	26	58.89	47.99	50.18	88.59	155.99	54.59
2005	24.06	17.29	34.6	142.62	128.53	25.85	46.24	36.75	83.78	68.61	63.38	26.03
2006	17.41	23.4	55.79	166.42	60.81	20.63	23.96	78.77	38.34	114.43	205.38	104.12
2007	31.4	25.58	36.62	120.21	86.84	71.16	66.3	58.75	90.64	89.85	81.92	34.53
2008	36.14	10.31	70.21	66.75	35.55	17.32	25.69	24.32	65.98	111.36	125.13	29.67
2009	37.54	18.12	27.89	83.47	58.65	20.25	15.02	28.28	21.76	107.32	73.31	63.71
2010	29.95	76.01	117.62	147.55	98.25	24.64	44.73	87.15	23.84	61.73	92.96	23.89
2011	13.99	20.55	55.13	92.5	65.6	60.04	69.23	98.15	55.58	131.7	209.12	57.64
2012	10.36	14.99	16.44	172.89	127.16	52	52.44	66.99	41.1	89.75	71.92	47.4
2013	32.03	7.21	74.63	233.34	58.2	39.13	42.47	51.5	55.24	44.67	111.81	46.26
2014	9.37	43.39	79.37	101.43	53.7	28.53	25.09	108.32	31.89	75.08	101.44	46.37
2015	14.16	22.54	35.57	213.54	64.37	17.26	26.03	24.01	16.03	80.39	145.51	84.85
2016	42.34	18.47	34.54	160.12	66.77	25.84	18.73	37.92	26.26	28.23	134.03	28.71
2017	10.15	32.44	20.75	63.9	88.67	17.9	32.99	53.4	33.54	103.7	142.09	17.3
2018	9.22	8.27	147.72	293.8	150.55	161.28	32.69	33.07	48.22	59.4	88.58	112
2019	30.67	15.34	21.23	95.71	94.42	101.26	31.54	47.58	62.5	172.55	246.55	110.88

Gauge 9

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	15.29	9.43	21.33	58.59	47.74	23.04	21.64	52.8	19.71	62.18	97.41	36.5
2001	64.78	12.86	97.94	133.01	44.51	45.24	32.93	50.61	31.76	69.57	118.49	27.98
2002	18.91	12.55	63.43	161.5	114	34.4	23.33	40.64	36.2	117.38	92.79	85.53
2003	14.66	13.95	46.74	173.38	133.17	21.11	27.99	117.67	23.42	121.16	84.96	43.36
2004	44.85	23.62	41.84	118.38	86.7	28.84	58.68	51.71	44.44	94.92	129.44	41.76
2005	20.54	19.95	36.22	123.13	126.19	25.76	43.45	37.12	69.02	76.07	48.16	21.12
2006	14.97	22.39	66.27	147.97	62.6	22.25	23.53	90.51	35.59	125.39	174.48	95.46
2007	29.5	28.16	30.29	101.87	97.38	79	72.15	69.87	76.92	101.27	66.87	26.32
2008	32.29	12.59	72.76	60.93	36.81	19.36	30.21	27.1	70.19	120.67	92.84	26.77
2009	28.66	20.76	27.77	78.04	54.34	24.05	14.75	32.81	19.28	131.63	62.27	61.98
2010	28.71	82.39	112.96	134.93	102.73	31.09	47.49	91.7	28.65	73.6	76.09	20.09
2011	13.36	20.84	52.69	89.37	66.76	60.83	65.48	126.44	55.82	144.78	180.94	48.08
2012	10.21	13.74	17.25	179.38	141.83	53.05	54.33	81.94	39.93	103.65	54.37	43.71
2013	27.85	7.57	75.41	201.64	69.56	54.62	47.25	66.11	55.54	53.55	95.64	45.03
2014	9.21	43.07	84.06	94.66	57.22	36.26	27.02	121.57	37.5	91.82	97.99	39.41
2015	13.84	22.72	38.06	195.23	72.71	26.61	29.25	27.65	17.05	106.81	112.64	73.74
2016	53.32	18.37	38.1	149.89	91.57	31.05	21.42	44.84	28.6	37.29	118.73	24.03
2017	10.05	32.65	21.5	75.83	98.08	20.81	38.96	76.94	35.81	138.79	143.2	15.31
2018	9.09	9.05	152	281.5	146.66	177.27	40.37	37.77	49.25	78.52	92.83	100.32
2019	29.86	15.68	21.51	89.85	112.4	103.05	33.96	69.13	54.4	217.09	199.52	104.16

Gauge 10

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	17.95	7.99	18.4	78.02	26.43	20.47	23.36	34.86	20.81	41.94	123.16	60.92
2001	73.96	9.99	94.49	123.65	33.31	49.36	33.03	38.6	26.42	39.86	137.79	42.53
2002	19	11.54	58.61	195.51	82.34	27.8	23.78	24.16	42.54	101.92	103.77	133.66
2003	16.04	14.15	52.77	225.19	95.77	19.9	27.96	77.04	36.18	94.77	105.58	59.72
2004	40.94	21.94	50.49	137.22	62.72	30.14	53.9	33.77	38.39	75.56	122.25	70.67
2005	27.52	13.09	28.09	147.24	87.28	30.75	41.81	40.16	52.41	60.26	65.66	27.23
2006	18.87	21.51	50.63	185.72	48.11	23.38	22.14	73.39	37.74	101.37	195.22	136.55
2007	31.43	18.58	43.14	130.99	58.65	65.73	64.59	38.72	60.98	73.87	77.31	40.95
2008	38.02	8.28	66.91	79.44	25.06	20.66	29.19	20.79	56.53	87.73	107.08	31.91
2009	41.64	14.25	26.86	79	44.54	22.04	19.97	20.6	20.82	113.12	67.51	75.06
2010	32.67	72.61	106.97	160.23	67.22	24.62	47.46	62.53	20.69	53.3	87.78	27.05
2011	13.87	20.14	45.65	107.74	55.15	55.8	68.24	75.25	50.8	116.2	208.62	62.48
2012	9.88	14.29	14.76	156.72	79.97	55.17	47.26	54.34	35.37	74.75	90.23	65.13
2013	31.77	8.64	78.49	265.83	30.8	49.86	39.36	33.21	36.97	36.26	115.05	55.27
2014	9.24	41.44	81.83	130.26	41.81	37.57	24.17	95.47	29.97	72.62	119.31	51.19
2015	14.63	19.15	40.29	261.3	50.99	20.73	33	20.13	14.46	77.82	160.71	101.41
2016	46.59	21.86	47.3	192.14	45.19	28.64	18.46	28.54	31.85	26.18	151.47	35.41
2017	9.7	36.61	23.79	76.31	59.83	21.38	24.44	35.84	29.3	98.26	162.24	24.38
2018	9.03	9.06	155.45	344.62	113.37	139.33	37.5	34.35	51.31	60.3	90.67	133.77
2019	32.94	15.82	23.15	119.87	71.89	105.32	29.81	39.74	61.06	168.46	234.48	167.84

Gauge 11

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	15.78	9.27	21.01	80.68	30.96	34.35	34.32	60.69	28.62	60.4	104.91	39.38
2001	66.07	11.63	96.02	136.73	39.96	74.31	48.11	58.39	36.79	55.69	114.42	28.26
2002	18.24	13.17	56.04	198.7	89.93	39.66	35.86	44.04	58.26	148.11	88.55	92.25
2003	13.96	16.56	56.08	230.76	110.23	28.1	41.88	124	44.5	129.18	89.06	42.57
2004	37.9	25.51	54.76	135.65	67.61	44.49	75.26	60.36	53.27	95.03	106.27	42.85
2005	26.74	14.64	30.8	151.21	100.58	43.4	63.72	69.79	69.67	88.4	54.5	16.7
2006	16.78	23.01	58.56	190.96	57.73	34.54	33.12	124.71	52.48	142.8	170.2	96.04
2007	29.08	23.26	42.46	132.34	76.2	97.84	96.97	71.48	84.43	107.46	65.34	27.61
2008	36.16	10.82	70.87	76.47	31.29	30.87	42.9	36.69	73.81	119.71	83.8	21.12
2009	36.7	17.49	30.03	88.7	47.66	33.66	28.66	44.81	28.01	144.85	58.79	50.69
2010	27.17	89.99	108.61	162.85	78.32	34.31	69.84	91.46	30.55	74.7	75.67	21.17
2011	12.76	27.36	50.13	126.27	64.13	80.74	96.54	131.03	75.26	156.24	176.9	41.46
2012	8.89	14.91	16.02	161.13	98.13	88.57	71.55	91.98	47.32	101.46	82.26	49.72
2013	28.62	9.6	85.44	275.22	36.32	75.83	61.58	60.24	52.34	57.42	102.62	38.67
2014	8.53	48.75	93.18	137.06	51.92	62.24	34.13	170.18	43.8	112.24	107.65	36.23
2015	13.47	24.36	44.03	284.37	63.7	33.01	48.33	37.79	20.07	111.17	147.3	68.01
2016	44.04	24.55	54.3	223.51	54.88	45.68	28.14	51.52	42.09	41.93	133.89	23.49
2017	8.98	42.35	27.65	80.5	67.78	31.99	39.95	70.21	42.85	159.18	135.62	16.93
2018	8.69	10.61	162.89	355.61	132.87	196.62	60.26	54.16	73.91	98.02	82.18	90.58
2019	30.23	18.96	27.37	128.72	87.43	141.14	42.75	77.7	68.36	258.8	196.49	104.18

Gauge 12

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	38.52	26.53	60.15	167.43	111.88	44.81	55.31	74.74	49.47	143.21	257.65	74.21
2001	151.82	33.49	191	283.74	134.83	91.94	74.32	72.44	55.87	130.25	279.92	54.59
2002	44.04	40.51	115.04	373.1	279.1	53.18	53.05	78.41	94.75	304.76	250.64	143.36
2003	32.25	41.22	113.4	407.82	345.37	44.41	61.85	129.31	71.03	297.33	215.51	82.14
2004	70.11	75.18	120.13	227.06	173.94	60.79	79.13	78.4	92.59	190.38	270.89	79.68
2005	42.45	34.49	76.26	241.8	311.43	61.2	101.26	102.24	94.43	202.9	139.63	31.36
2006	38.32	54.66	171.93	313.65	222.74	47.45	55.65	129.57	92.74	328.96	432.77	202.14
2007	77.44	56.44	96.61	221.03	248.59	117.19	147.7	119.26	101.52	297.95	174.02	59.81
2008	82.32	33.2	168.23	163.08	90.04	43.07	71.53	55.15	89.74	248.81	215.28	39.07
2009	70.16	52.5	83.34	183.64	158.89	50.3	39.85	57.52	44.47	305.44	175.8	102.04
2010	54.38	218.42	227.28	248.54	248.89	47.33	88.83	107.05	39.86	174.32	196.54	42.24
2011	32.82	66.45	122	238.96	192.9	88.19	127.49	155.37	126.57	319.9	382.54	90
2012	23.77	32.87	43.58	349.49	350.79	100.47	107.47	128.57	67.54	240.16	190.83	107.16
2013	58.63	23.69	152.73	413.24	105.34	72.05	90	105.23	77.21	113.93	237.8	64.58
2014	19.99	123.39	205.42	221.79	147.26	85.97	53.06	203.38	73.58	219.9	232.52	69.11
2015	31.29	52.9	93.79	471.37	196.48	37.97	70.26	55.14	33.09	264.6	328.45	119.22
2016	113.59	49.8	102.85	368.65	153.23	56.78	44.74	82.12	57.56	80.34	282.61	39.49
2017	21.31	87.21	57.16	144.11	189.2	31.91	65.13	111.81	75.23	292.1	313.4	30.07
2018	22.6	28.1	372.68	629.19	443.82	181.07	88.76	55.54	111.66	191.47	206.05	171.05
2019	71.27	44.95	54.8	231.84	231.57	148.17	59.72	100.84	106.23	564.64	427.32	192.76

Gauge 13

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	36.94	22.16	47.84	166.2	103.92	44.5	51.09	70.67	43.7	137.59	255.53	73.58
2001	153.36	27.69	161.81	268.84	120.41	83.4	73.95	75.48	51.98	120.53	276.64	53.89
2002	41.88	33.19	96.31	346.61	264.96	47.83	49.64	68.13	84.44	294.62	239.69	149.14
2003	31.88	36.54	96.28	411.96	331.68	42.37	61.02	138.56	65.22	278.67	206.32	85.16
2004	69.16	62.19	100.63	235.47	173.7	63.2	84.65	82.03	82.14	179.54	251.54	80.79
2005	44.25	28.73	61.38	238.48	294.52	59.51	100.58	99.72	85.51	189.99	136	31.62
2006	36.65	46.84	139.63	302.42	207.82	43.95	49.85	143.05	82.21	311.26	404.75	194.13
2007	70.98	44.29	76.42	202	222.85	100.99	143.37	113.18	93.85	268.02	164.5	56.99
2008	70.92	26.41	128.13	157.08	84.72	39.67	65.3	53.33	85.24	240.79	206.76	39.77
2009	68.24	41.8	64.09	171.68	141.29	45.38	38.03	61.46	41.64	297.05	162.96	97.6
2010	54.95	170.92	187.11	242.81	236.65	41.47	87.34	109.81	40.05	163.71	187.35	41.17
2011	30.91	56.68	100.06	249.96	177.98	95.13	133.96	160.01	115.25	298.27	357.94	88.5
2012	21.72	28.57	35.13	327.92	303.43	88.45	96.72	125.15	65.27	202.46	182.73	98.22
2013	53.54	18.17	118.2	396.93	89.15	71.71	85.17	95.26	74.03	102.39	218.88	63.32
2014	17.27	102.5	155.4	199.28	127.86	75.18	48.85	220	65.23	204.58	216.72	62.33
2015	27.06	44.55	69.13	431.22	162.48	34.68	65.19	52.64	29.66	223.35	294.84	118.75
2016	96.62	42.4	75.13	341.42	133.49	51.5	40.55	74.89	53.22	73.09	274.85	37.7
2017	18.32	75.2	43.37	122.3	149.42	33.08	64.65	103.69	66.95	253.26	289.39	29.74
2018	18.07	21.7	286.68	582.67	351.94	195.45	81.93	55.49	101.18	186.46	183.43	167.85
2019	59.97	38.34	40.23	211.06	201.45	151.24	53.65	106.94	95.39	481.05	400.62	173.99

Annex 4.2: Mean Monthly Discharge (2000 – 2007)

Annex 4.2.1: Nanyuki River

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	0.953	0.420	0.762	6.937	6.732	6.678	3.305	2.746	0.993	8.444	3.401	2.512
2002	0.720	0.612	0.443	1.935	1.394	1.873	0.681	1.966	0.222	6.877	2.836	1.835
2003	0.673	0.188	0.211	1.181	2.582	2.156	1.064	1.505	1.967	2.325	5.388	2.453
2004	1.024	0.682	0.485	0.498	0.519	0.544	1.032	1.093	1.081	2.692	4.159	1.901
2005	0.359	0.197	1.114	1.226	1.389	1.148	1.324	4.735	2.776	4.452	1.410	0.853
2006	0.664	2.693	2.881	4.526	1.402	2.553	3.674	10.404	5.876	19.224	15.188	3.674
2007	1.925	0.904	0.034	5.417	15.728	10.695	1.049	1.274	1.197	4.283	1.020	0.832

Annex 4.2.2: Timau River

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.046	0.044	0.033	0.029	0.163	0.053	0.026	0.050	0.026	0.067	0.157	0.043
2001	0.085	0.018	0.032	0.084	0.165	0.096	0.131	0.110	0.086	0.031	0.198	0.153
2002	0.071	0.041	0.054	0.098	0.199	0.118	0.057	0.100	0.092	0.096	0.322	0.109
2003	0.079	0.042	0.024	0.038	0.396	0.148	0.207	0.199	0.196	0.078	0.059	0.093
2004	0.055	0.045	0.054	0.229	0.067	0.036	0.112	0.171	0.120	0.069	0.620	0.169
2005	0.048	0.040	0.038	0.119	0.355	0.202	0.091	0.094	0.090	0.087	0.088	0.045
2006	0.032	0.022	0.033	0.229	0.067	0.036	0.112	0.147	0.208	0.192	0.243	0.271
2007	0.201	0.092	0.047	0.124	0.178	1.320	1.249	1.003	0.732	0.841	0.499	0.141

Annex 4.2.3: Likii River

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002	0.706	0.301	0.353	0.634	2.122	0.556	0.331	0.578	0.353	1.197	1.704	0.946
2003	0.742	0.190	0.165	1.432	2.166	0.878	0.774	0.936	1.093	1.095	2.004	1.224
2004	0.682	0.232	0.262	1.366	0.719	0.318	0.323	0.794	0.684	1.196	1.812	0.920
2005	0.252	0.078	0.054	0.222	1.635	0.627	0.544	0.616	1.325	0.842	0.636	0.398
2006	0.213	0.037	0.204	0.994	1.387	0.712	0.575	1.223	1.271	1.077	2.465	1.118
2007	0.989	0.643	0.123	0.572	0.911	1.621	1.501	2.292	2.272	1.338	0.781	0.288

Annex 4.2.4: Ontulili River

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.044	0.309	0.961	1.159	1.097	0.249	0.052	0.455	0.197	0.544	0.329	0.119
2001	0.121	0.073	0.063	0.323	0.862	0.511	0.555	0.610	0.461	0.086	0.484	0.876
2002	0.182	0.084	0.035	0.056	0.648	0.125	0.097	0.124	0.071	0.251	0.520	0.154
2003	0.133	0.040	0.028	0.289	0.809	0.580	0.336	0.399	0.467	0.324	0.865	0.323
2004	0.105	0.090	0.055	0.473	0.296	0.051	0.044	0.155	0.367	0.288	0.966	0.269
2005	0.046	0.030	0.024	0.027	0.684	0.411	0.294	0.310	0.613	0.366	0.259	0.137
2006	0.075	0.010	0.022	0.242	0.395	0.060	0.113	0.760	0.796	0.465	1.235	0.527
2007	0.256	0.060	0.030	0.083	0.312	0.638	0.657	1.274	1.644	0.626	0.222	0.032

Annex 4.2.5: Nanyuki_1 River

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.081	0.018	0.016	0.045	0.200	0.057	0.095	0.334	0.274	0.267	0.358	0.195
2001	0.267	0.082	0.108	0.375	0.396	0.333	0.395	0.332	0.139	0.238	0.619	0.261
2002	0.231	0.039	0.078	0.368	0.686	0.176	0.059	0.113	0.028	0.257	0.389	0.246
2003	0.189	0.023	0.021	0.640	0.836	0.259	0.216	0.243	0.271	0.339	0.488	0.241
2004	0.235	0.040	0.080	0.381	0.161	0.128	0.097	0.234	0.134	0.466	0.422	0.227
2005	0.040	0.005	0.085	0.341	0.088	0.102	0.074	0.051	0.048	0.034	0.019	0.057
2006	0.519	0.278	0.159	0.034	0.261	0.346	0.192	0.668	0.405	0.376	0.286	0.012
2007	0.280	0.309	0.397	0.376	0.507	0.453	0.358	0.515	0.460	0.264	0.008	0.062