ADDIS ABABA UNIVERSITY

AFRICA CENTRE OF EXCELLENCE FOR WATER MANAGEMENT (ACEWM)

Reservoir Operation for Optimal Water Use: A case study of Kabalega reservoir in Uganda

By;

Chelangat Cyrus

July, 2020

Addis Ababa

ADDIS ABABA UNIVERSITY

AFRICA CENTRE OF EXCELLENCE FOR WATER MANAGEMENT

(ACEWM)

Reservoir Operation for Optimal Water Use: A case study of Kabalega reservoir in Uganda

By;

Chelangat Cyrus

Supervisor

Dr. ing Adane Abebe

(Associate professor)

A thesis submitted to Africa Center of Excellence for Water Management in partial fulfillment of the requirements for degree of master of science in Water Management (Hydrology and Water Resources)

July, 2020

AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT

ADDIS ABABA UNIVERSITY

Reservoir Operation for Optimal Water Use: A case study of Kabalega reservoir in Uganda

A MASTERS THESIS SUBMITTED

TO

AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT

THESIS APPROVAL FORM

APPROVED BY BOARD OF EXAMINERS

This is to certify that we the undersigned, have examined this MSc Thesis and that in our opinion; it is fully adequate, in scope and quality, as a MSc thesis for the Degree of Master of Science in Water Management (Hydrology and Water Resources)

Advisor

Name: **Dr. Ing. Adane Abebe**

Signature.................................... Date 10/07/20

Examiners

Name: **Dr. Andinet Kebede**

Signature....................................Date July 09, 2020

Name: **Dr. Mebruk Mohammed**

Signature.................................... ....Date July 09/20

DECLARATION

I Chelangat Cyrus declare that, this thesis is my work with all sources of materials used for this thesis development being duly acknowledged. The thesis is submitted in partial fulfillment of the requirements for a degree of Master of Science in Water Management (Hydrology and Water Resource) of Addis Ababa University.

Signature………… ………………………………………..

Date 13th/July/2020……………………………………………………….

ACKNOWLEGMENT

I would like to express my sincere gratitude to Africa Centre of excellence for Water Management staff members and all her lecturers in their various capacities.

Special thanks to my main supervisor/advisor Dr. Ing- Adane Abebe for his valuable guidance, encouragement, suggestions and constructive comments from begining to the completion of this research work.

I would also acknowledge the following ministries and authorities in Uganda; Ministry of Energy, Uganda National Meteorological Authority, Ministry of Water and Environment- Directorate of Water Resources, Electricity Regulatory Authority and Hydromax company limited for the support they offered towards data acquisition for this research.

Much appreciation also goes to Ndejje University Department of civil engineering for hosting me under exchange visit program in collaboration with Africa Centre of excellence for Water Management.

ABSTRACT

Wambabya River catchment over the past years (since 2013) has been experiencing alterations in its upstream (forests cleared for agriculture) which may have resulted in seasonal variability in rainfall pattern. Temperatures have increased and thus high-water loss through evapotranspiration. River inflows into the reservoir have decreased thus affecting the power generation from Kabalega dam as evidenced by the operation below its capacity in most of the first quarter months of the year and thus being unable to meet the power demand and downstream ecological requirement. The study developed reservoir operation policies for optimal water use of Kabalega reservoir in order to meet the target demands. Australian Water Balance Model (AWBM) was used to simulate Wambabya River inflow into Kabalega reservoir. The model was calibrated with observed flow from 1990-2009 and validated with flow from 2010-2019. Nash & Sutcliff efficiency for calibration and validation is 0.758 and 0.67 respectively. HEC-ResSim model was used to optimize and develop new reservoir operating rules by calibrating and validating the model for 5 and 3 years which yielded Nash Sutcliff coefficient and correlation coefficient of 0.85 and 0.82 respectively. respectively. The reservoir system performance was further investigated by using statistical performance indices which are; reliability, vulnerability, resilience and sustainability index. Simulated releases were compared to the actual releases and generated/ simulated power compared to power demand and it was found that the system exhibits fewer deficits in terms of power supply, with minimal spill flows over the spillway found to occur compared to the original operation policy. The derived operation policies are thus recommended to serve as decision-making tools for operation of Kabalega reservoir to maximize the benefits.

Key words: Australian Water Balance Model, HEC-ResSim, Kabalega reservoir, Operation policy, Uganda.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AWBM	Australian Water Balance Model
HBV	Hydrologiska Byråns Vattenbalansavdelning
HSPF	Hydrological Simulation Program- Fortran
KINEROS	Kinematic Runoff and Erosion Model
MIKE SHE	MIKE System Hydrologique European
NWSRFS	National Weather Service River Forecast System
PIHM	Penn State Integrated Hydrologic Modelling System
ResSim	Reservoir Simulation Model
SWAT	Soil and Water Assessment Tool
TOPMODEL	Topography based Hydrological Model
UMWOE DWR	Uganda Ministry of Water and Environment, Directorate of Water Resources
UNMA	Uganda National Meteorological Authority
VELMA	Visualizing Ecosystem Land Management Assessments
VIC	Variable Infiltration Capacity Model.

1.0 INTRODUCTION

1.1 Background

Water resources scarcity is one of the most prevalent natural resource allocation problems faced by the water users and policy makers in the world (Winpenny, 1994). Consequently, the economic development and economic sectors that rely on water resources are experiencing fierce competition and conflicts among different water users. The negative impacts brought by water scarcity range from residential impacts, industrial impacts and agricultural production inconvenience, to poor aesthetics, health, and safety of the people (Shiau & Lee, 2005). Goodarzi et al., (2013) proposed the adoption of appropriate policies which ensure efficient water use in various sectors. Therefore, new strategies are appropriate to ensure efficiency and effectiveness in the development and management of water resources (Debnath et al., 2009). This can be achieved through optimal water resources allocation systems that can maximize set objectives like hydroelectric power generation (Mujumdar & Nirmala, 2007), crop yield (Reddy & Kumar, 2006) and flood control (Sharma et al., 2016). Allocation of water optimally requires the consideration and apportioning of water equitably to all the water users. Rani & Moreira (2010) recommended consideration of the hydrological response and current reservoir system to effectively manage the reservoir and its strategies. This is premised on the fact that hydrological conditions are the main drivers which affect directly the reservoir operational decisions made because of their variability and structural uncertainty.

Amirhamzeh, (2012) proposed that River reservoir systems require specific operational strategies which serve as practical guides for water storage and/or releases. This ensures that human demands for water, flood control and other objectives of reservoir operation management are achieved. The problem of insufficient water supply during periods of low flows can be overcome through drawing attention to improving water resources management, particularly in the optimization of reservoir operations (Chang et al., 2005).

Simulation modelling is among the most effective ways of analysing water resource systems. simulation models operate basing on physical relations comprising of series of operational rules to simulate the behaviour of the system and new conditions under a specified policy (Ziaei et al., 2012). In spite of the development and growing use of optimization techniques, simulation models remain prominent tools in practice for reservoir system planning and management studies. They are mostly used to examine and evaluate the performance of complex water resources systems. Series of runs are developed to compare system performance for alternative reservoir configurations, storage allocations, demand levels, operating rules, and/or hydrologic inflow sequences (Wurbs, 1993). Simulation models provide an insight on how the real system is likely to perform over time under various conditions (Ziaei et al., 2012). These models may be deterministic or stochastic, time sequenced or event sequenced. Optimization models mostly compute reservoir releases that optimize an objective function without directly addressing the finer details of operating rules.

According to Wurbs (2005), the most popular simulation modelling Software so far used in several studies and projects for reservoir simulations include; Riverware (Zagona, et al.,), MODSIM (Labadie, 2006), MIKEBASIN (DHI, 2003) and HEC-ResSim model (Klipsch & Hurst, 2007). Many studies have applied HEC-ResSim model and yielded appealing results for example (OLani, 2006), (Asefa, 2011), (Lara et al., 2014), and (Jebbo & Awchi, 2016). Mariam, (2012) built a simulation model for Tekeze dam reservoir in Ethiopia to find out the optimal operation policy for the production of hydroelectric power and for the fulfillment of the requirements at the downstream of the dam. The wide application of HEC-ResSim is linked to its advanced built in features such as outlet prioritization, scripted state variables, and conditional logic which make it feasible to model more complex systems and operational requirement of existing and proposed reservoirs (Uysal et al., 2016). The model also has the capability of providing the spillway discharges in terms of gate opening through detailed representation of the gate management on the level of the individual gates.

Seasonal variability in rainfall pattern and temperature increases (leads to high-water loss through evapotranspiration) in Wambabya River catchment have negatively impacted the river inflows into Kabalega reservoir. This variability could be attributed to rampant deforestation and overgrazing rampant in the upstream of the catchment. The impacts are being experienced because poverty has driven the poor community to over exploit the natural resources in a way that is damaging the environment. Due to this, the water resources, especially the rivers, have dwindled (WWF, 2006). The constructed reservoir across River Wambabya is thus unable to meet the power demand and downstream ecological requirement in most of the first quarter months of the year.

Rainfall, temperature and evapotranspiration changes affect availability of water resources and demands, and thus the performance of reservoir- based systems. Accommodating these changes in the water resources situation requires substantial improvement in reservoir operating policy water use and management efficiency. The operation policy will guide reservoir operators on how much and when to release water (Mamman, 2018).

To elude water scarcities that result in under operation of dams, depress downstream users and damage ecological environment, a large share of water to meet the demands must come from water saved from existing uses. This can be done through comprehensive reform of water policy with dam and reservoir operation rules, and integrated management as a primary approach to address the sustainable water resources both for subsystem and river basin level**.** This study is therefore aimed at simulating river inflow to Kabalega reservoir, modifying and recommending optimal reservoir operation rule curves and assessing Kabalega reservoir performance under various reservoir operating policies.

1.2 Problem Statement

The catchment of Wambabya River in lake albert basin supports the community with water for livestock and domestic use, hydroelectric power generation and for maintaining the ecology. The dominant economic activities in the catchment are; Agricultural activities, over stocking of livestock and deforestation.

Catchment alteration has been on an increase over the past years till present. Its forests and vegetation at the upstream have been cleared for agriculture and settlement. Furthermore, the permanent and seasonal wetlands have been encroached and set upon fire to support pastoralists' livestock and act as refugia for cultivation during the dry season. In so doing this, the wetlands have lost their water storage capacity. The catchment has been experiencing these due to an influx of immigrants of people from highly populated areas like Kabale, West Nile in Uganda and from the neighboring country, Democratic Republic of Congo (WWF, 2006). Because the new arrivals of immigrants have no attachment to any land and they have to survive, they end up encroaching and degrading the environment by carrying out deforestation, pit sawing, poor soil husbandry and cultivating near rivers.

These have resulted into extreme hydrological variability and seasonality of rainfall and runoff within the catchment. Temperature increase has too increased the water loss through evapotranspiration (Masindi District Environment Department, 2005). River flows have decreased resulting into under operation of the Kabalega dam (built across River Wambabya) in most of the first quarter months of the year. Benefits reaped from hydroelectric power have been lowered, the ecological environment and water users downstream of the dam have too been affected. This therefore calls for new reservoir operation policies so as to achieve the target demand, meet the minimum downstream ecological requirements and above all maximize the reservoir benefits.

1.3 Research Objectives

This research comprises of the following main and specific objectives which guided the entire research process.

1.3.1 Main objective:

The main objective of the study is developing reservoir operation policies for optimal water use of Kabalega reservoir.

1.3.2 Specific objectives

- To simulate river inflow to Kabalega reservoir in Wambabya River catchment.
- To revamp/modify and recommend optimal reservoir operation rule curves for Kabalega reservoir.
- To assess Kabalega reservoir performance under various reservoir operating policies.

1.4 Significance of the study

Kabalega reservoir was purposely constructed to store water for generation of hydroelectric power, provide ancillary protection to downstream towns against flooding and ensure minimum environmental flow downstream. This study will generate a reservoir operation policy that will serve as a decision-making tool to regulate the reservoir system under varying hydrological conditions to attain an optimal water allocation and balance between net benefits of hydropower generation and downstream water users and ecological environment. Since no research has been carried on this dam ever since it was commissioned, this study will also serve as a baseline for conducting further studies in the catchment or be a reference while carrying out similar studies in other catchments.

1.5 Scope and delimitation of the study

The study was limited to developing appropriate reservoir rule curves and assessing the performance of Kabalega reservoir under various reservoir operating policies.

The study does not consider the effect of climate change on reservoir operation. It did not employ penman Monteith method for determining evapotranspiration within the catchment due to inadequate data. Additionally, the study did not consider the effect of the sediment yield on the live storage of the reservoir.

2.0 LITERATURE REVIEW

2.1 Water storage

Reservoirs are categorized among the efficient and effective measures of an integrated water resource development and management as they have performed progressively viable roles in balancing the conflict between social development and water resources scarcity by storing water for various purposes (Guo et al., 2004). Water impoundment by a dam creates a reservoir in which water is stored and used to serve multiple purposes. Reservoirs regulate the natural stream flow through storage of excess water during the high flow season to control downstream flooding of an area and release the stored water during the dry season of the year to meet various target demands. According to USACE (2007), reservoirs serve a wide range of purposes which may include; flood risk management, navigation, hydropower, water supply for municipal and industrial, water quality, irrigation, fish and wildlife, low flow augmentation, and recreation.

2.2 Reservoir operations and policy

Reservoir operation as an important part of water resources planning and management involves specific guidelines which have to be developed early in the planning stage of a project and be reformed later based on actual operational experience. These guidelines are either rigid rules which are to be exactly followed by the dam operator, or flexible guidelines that permit considerable decisions to the taken by the dam operator. They can be graphical, tabular, or narrative in form or a combination of these (Jain & Singh, 2003).

Reservoirs are operated according to a set of operations which comprise of rules or guidelines that allow the water to be either stored or released depending on the purposes required to be served at a particular period. These decisions regarding water release or storage in different time periods is made in accordance with the available water, inflows to the reservoir, target demands, and time of the year. Single purpose operated reservoirs are usually affected with decision challenge of the release amount to be made from the reservoir to maximize the purposed benefits and for multipurpose reservoirs, additionally, optimal allocation of water released among all the purposes is required. The complexity of a reservoir operation problem is dependent on the compatibility of the various intended purposes. If they are compatible, less effort is needed for coordination. Efficient operation of multiple reservoirs requires a high degree of intelligence, intuition, and experience to ensure that they are not left partially empty at the end of the rainy season, or be found full at the time of arrival of a series of peak floods, which lead to heavy releases causing floods in the downstream areas (Mamman, 2018).

Reservoir operation policy

Reservoir operating policies are based on dividing the total storage capacity into designated pools or vertical zones. The pools include inactive pool, conservation pool, flood control pool and surcharge pool. They regulate the release of water from storage at any time of the year depending on the reservoir state, likely inflows to the reservoir, water demands, release capacity, and downstream constraints for example, the river channel capacity (KKhan & Tingsachali, 2008). The reservoir operation policy guide the reservoir to ensure improved overall performance in terms of its reliability and vulnerability. Loucks & Beek, (2007) in their study suggested two sorts of operating policies; one which differentiates the target water storage for a selected time and the other which categorizes the reservoir storage zones exercising various rule curves that are correlated by specific distribution policies.

Rigid Operation Schedules

These operation schedules are required in reservoir operation mostly when urgent decisions are to be taken but the required detailed data are not available or there is not enough time to analyse the existing data. These urgent decisions are usually made in a situation like in flood management. These schedules for flood control operation in a gated reservoir are mostly used by non-technical operators at the dam site. Since these schedules are derived based on the study of the design flood or the probable maximum flood, they are dependent on reservoir elevation data, river stage at a downstream point, inflows to the reservoir, and the rate of change of reservoir elevation. All these data are made available to the dam operator even when all means of communication break down (Jain & Singh, 2003).

Standard Linear Operating Policy (SLOP)

According to this operation policy, when in a certain period the amount of water stored is less than what is demanded, all the available water in the storage is released. If the available water exceeds the target demand but less than target demand plus available storage capacity of the reservoir, water only equal to the target demands is released and the surplus water stored in the reservoir. In case, even after making water releases equivalent to the target demands, there exist no reservoir space for storage of the excess water, all the water in excess of the maximum storage capacity of the reservoir is released (Jain & Singh, 2003). This release of water in excess of the reservoir capacity is to avoid dam collapse and safe guard the downstream areas from flooding. This policy is mostly used in planning studies particularly for firm yield studies but is rarely used in day-to-day operation because of its rigidity. However, (Revelle, 1999) proposed the use of a rationing rule to minimize the drawback caused by this rule especially in the event of drought.

2.3 Rule curves

The operation of a reservoir, when performed in accordance to the set rules for balancing supply and demand for water can mitigate conflicts among water users. Rule curves are among the most commonly used tools to aid the operation of reservoirs. (Bravo et al., 2006) defined these curves as the useful division of the volume of a reservoir in zones each with different policy for water supply for different uses. Operating rule curves express the operation strategy of a reservoir in a visual way (Chang et al., 2005). The curves are subject to some implicit constraints for example, the continuity between consecutive time periods and the categorically increasing relationship between reservoir releases and storage or available water. These advantages have prompted the wide application of operating rule curves in practice. Although the term "rule curve" denotes various other types of storage volume designations as well, the top of conservation pool is a common form of rule curve. It is varied seasonally at many reservoirs, particularly in regions with distinct flood seasons. The top of conservation pool could sometimes be varied as a function of watershed conditions, forecasted inflows, floodplain activities, storage in other system reservoirs, or other parameters as well as season of the year.

Several studies regarding the use of rule curves have been evolving since the 1960s, when this tool started to be applied incorporating new aspects of modern water management in operational routines of reservoirs. Among these aspects are, climate change (Lee et al., 2011), ecological flows (Zhou & Guo, 2013) and negotiation of conflicts between water users (Chang et al., 2010). Advances in the systems analysis methods have also been incorporated into the determination of rule curves, these include; multi-objective approaches (Chang et al., 2010) and meta-heuristics (Taghian et al., 2014). Rule curves specify the desired storages to be maintained in a reservoir as closely as possible during different times of the year while trying to meet various demands. The inferred assumption is that a reservoir can best satisfy its purposes provided that the storage levels specified by the rule curve are maintained in the reservoir at different times.

Release rules are usually derived from trial and error simulations. Performing these simulations requires at least an imprecise idea of the expected impact of different alternative policies on various system performance measures or objectives. These Policy objectives could be the maximization of expected annual net benefits from downstream releases, reservoir storage volumes, hydroelectric energy and flood control, or the minimization of deviations from particular release, storage volume, hydroelectric energy or flood flow targets or target ranges (Mamman, 2018).

Rule Curves derivation

Rule curve derivation is dependant on the reservoir type and the purposes to serve. For example, a reservoir may be a seasonal reservoir or a multi-annual reservoir type. With a seasonal reservoir, the storage is utilized to store water from the wet season to the dry season, whereas in a multi-annual reservoir, storage is used to impound water from a wet period to a subsequent dry period which could occur several years later (Jain & Singh, 2003). Several optimization and simulation models have been developed to derive these curves. Amirhamzeh, (2012) used genetic algorithm to derive a single reservoir operation rule curve. OLani, (2006) applied HEC-ResSim simulation model in Wadecha – Belbela reservoirs to establish water release guide rules to the irrigation schemes under inflow scenarios. These rule curves are mostly derived through operation studies by use of historic or generated flows.

Guide Curve Operation

Guide curve in HEC-ResSim is a target elevation of a reservoir which can be illustrated as a function of time. It regulates releases so that a certain storage level is maintained by releasing water as quickly as possible when high inflows encroach into the flood pool and raise storage above the guide curve, or curtail releases to the minimum required amounts necessary to satisfy conservation, or hydropower requirements when inflows are low and storage level is drawn-down below the guide curve (Klipsch & Hurst, 2007).

Hydroelectric Power Operations

Hydroelectric plants are generally used to complement the other components of an overall electric utility system. The plants can assume load rapidly and are very efficient for meeting peak demand power needs but water availability generally is a limiting factor in energy generation. The objective of an electric utility is to meet system demand for energy, capacity (power), and reserve capacity (for unexpected surges in demand or loss of a generating unit) at minimum cost (Wurbs, 1991).

Hydroelectric plants may be classified as storage, run-of-river, or pumped storage. A storage-type plant has a reservoir with sufficient capacity to permit carry-over storage from the wet season to the dry season or from wet years through a drought. A run-of-river plant has no active storage, except possibly some pondage to permit water storage during off-peak hours for use during peak hours of the same day or week, but may have a significant amount of inactive storage which provides head. Flows through the turbines of run-of-river plants are limited to unregulated stream flows and releases from upstream reservoirs. A pumped-storage plant generates energy for peak load, but during off-peak periods, water is pumped from the tailwater pool to the headwater pool for future use. The pumps are powered with secondary energy from some other plant in the system (Wurbs, 1991).

2.4 Hydrological models

Hydrological models refer to the simplified illustrations of part or entire system of the hydrological cycle (Sorooshian & Hamid, 2008). These models require the runoff generation and the runoff routing component as they are the essential components. The runoff generation component determines how much of a rainfall becomes part of the storm hydrograph whereas the runoff routing component takes account of the distribution of that runoff in time to form the shape of the storm hydrograph (Beven, 2012). The model is most preferred if it gives results close to reality with the use of both least parameters and model complexity. Runoff models are sets of equations that perform runoff estimation as a function of a variety of parameters used for describing characteristics of a watershed. Rainfall data and drainage area are two important inputs required for all models. Other inputs to the model are; watershed characteristics which include soil properties, vegetation cover, watershed topography, soil moisture content, characteristics of ground water aquifer (Pechlivanidis et al., 2011). Generally modelling using rainfall-runoff models requires attainment of accurate parameters for calibration process in order to obtain actual representation of the hydrological process. The parameters are obtained through optimisation which is based on several assumptions. It assumes that the observations with which the simulations are compared with, are error free and that the model is a true representation of that data. Inconsistency between measured rainfalls and discharges, or incommensurability between observed and predicted soil moisture variables also affects the attainment of optimum model parameters (Beven, 2012).

Hydrological models may be classified based on nature of algorithms (empirical, conceptual and physically based), nature of input and uncertainty (deterministic and stochastic), nature of spatial representation (lumped, semi distributed and distributed), and based on the type of storm event-single event and continuous event (Sorooshian & Hamid, 2008).

2.4.1 Empirical models

Empirical models sometimes called data driven models are such models which take only the information from the existing data without considering the features and processes of hydrological system. These models are valid only within the boundaries and they are best used when there is need to determine the distribution of runoff values between upstream and downstream boundary. Because of their simplicity in analysis, they have been applied to ungauged watersheds by regional analysis relating model parameters to physical and climatic descriptors of the catchment (Pechlivanidis et al., 2011). Very few parameters are needed, Simple to implement, it has a quick computational time, and being cost effective are reasons that make data-driven models easy to use and thus be chosen for modelling (Dawson & Wilby, 2001). One drawback of these model process is that it at times leads to contrasting conclusions than what accepted theoretical analysis would suggest (Beven, 2012). These models include; Soil Conservation Service Curve Number, regression equations, and machine learning used by Artificial and Deep Neural Networks. The assumption of the ratio of actual runoff to potential runoff is equal to the ratio of actual to potential retention used by curve number has no physical justification.

2.4.2 Conceptual models (Parametric models)

These models consist of a number of interconnected reservoirs which represent the physical elements in a catchment. These reservoirs are recharged by rainfall, infiltration and percolation and emptied by evaporation, runoff and drainage. The water balance equation represented by these models involves the transformation of rainfall to runoff, evapotranspiration and groundwater (Vaze et al., 2011). They are easy to use, calibrate and are appropriate to use when computation time is limited and watershed characteristics are not analysed in detail. Its drawback is the need for a variety of parameters and meteorological input data. Examples of conceptual models are; TOPMODEL (Beven et al., 1984; Beven & Kirkby, 1979), National Weather Service River Forecast

System (NWSRFS), HBV model (Bergström, 1992) and Hydrological Simulation Program- Fortran (HSPF) (Donigian *et al.*, 1995).

2.4.3 Physically based models (mechanistic models)

These are mathematically idealized representations of the real phenomenon that include the principles of physical processes. It constitute the component hydrological processes of evapotranspiration, infiltration, overflow, and saturated and unsaturated zone flow using the governing equations of motion which are usually formulated as non-linear partial differential equations based on continuum mechanics (Pechlivanidis et al., 2011).The models use state variables which are measurable and are functions of both time and space (Vaze et al., 2011). The connection between model parameters and physical catchment characteristics is one of the greatest strength of a physical model which make it more realistic. These models produce better results given that the input data is accurate, physical properties of the hydrological processes are accurately understood and applied on fine scales because of the computational time. These models require large amounts of data to run which limit their usage (Uhlenbrook et al., 2004). In a bid to reduce computational burden and data requirements, simplified physics are sometimes used to represent the physics for example the simplified St. Venant equations and the Green-Ampt equation (Pechlivanidis et al., 2011). Examples of these models are; Visualizing Ecosystem Land Management Assessments (VELMA), Variable Infiltration Capacity Model (VIC), MIKE System Hydrologique European (MIKE SHE) (Refsgaard & Storm, 1995), Penn State Integrated Hydrologic Modeling System (PIHM), Kinematic Runoff and Erosion Model (KINEROS) (Ranch & Simonovic, 1995).

Classification based on the nature of spatial representation:

Lumped models treat the catchment area as a single homogenous unit as the characteristics of the catchment are set to be equal for the entire area of the watershed which more often results into either over or under parameterization (Rinsema et al., 2014). They are expressed by differential or empirical algebraic equations, considering no account of spatial variability of processes, inputs, boundary conditions and catchment geometric characteristics. These models calculate a single runoff output value at the river outlet point of the watershed. The models adequately simulate average runoff conditions with fast computational times as they are designed to simulate total runoff and streamflow at the outlet point, not specific flows within a catchment. Examples include Empirical and conceptual models, and machine learning.

Semi-distributed models are modifications of lumped models, with characteristics of distributed models. The model's process splits the entire catchment into sub catchments, each with different parameters (Rinsema et al., 2014). Runoff is calculated at the pour point of each sub-catchment considering spatial variability and land use characteristics without an overwhelming model structure (Kokkonen et al., 2001). These models have a fast computational time, ability to use less data and fewer parameters than a distributed model (Pechlivanidis et al., 2011). Input data manipulation is common in these model type. For example, an average of spatially distributed rainfall data must be obtained within the sub-catchment, or recorded rain gauge data at specific locations must be distributed to the area by using the Thiessen Polygon method. Examples of these models include TOPMODEL (Beven et al., 1984; Beven & Kirkby, 1979), SWAT (Anorld, et al 2012) among others.

Distributed runoff models discretize the catchment into small grid cells and solves the equations for the state variables associated with every grid cell of the catchment. They are the most complex models as they account for spatial heterogeneity in inputs and parameters. The drawbacks of the model are; data-intensity, with all the input data distributed spatially and temporally, and too much demand for calibration of parameters for every grid cell. The model's computational time to perform one simulation varies from one minute to several hours depending on the input data, catchment size and computational constraints (Vaze et al., 2011). This model's difficulties, when compared to lumped models, is the reason why distributed models are not widely used in modelling runoff (Rinsema et al., 2014). Examples are Physically distributed models are MIKESHE (Refsgaard & Storm, 1995) and VELMA.

Rainfall runoff models are mostly selected basing on the project objectives, availability of the data, study size, output needed, and the desired simplicity. For example, when dealing with a watershed with high rates of infiltration thus low or little overland flow, a model that only calculates overland flow while ignoring subsurface flow is not appropriate (Knapp et al., 1991). Vaze et al., (2011) stated that model selection is tied to uncertainty in model results due to the assumptions and simplifications each model incorporates. Models with many parameters have less chance of finding the best parameter than models with fewer parameters (Rinsema et al., 2014). Bashar et al.,(2005) in his study at the Nile River Basin concluded that simple models that involve fewer parameters forecasted discharge better than those that used more parameters and complex mathematical computations.

Some Rainfall-runoff models include Australian Water Balance Model (AWBM) (Boughton, 2004), Sacramento, SIMHYD – Simplified form of HYDROLOG, TANK and Soil moisture accounting and routing (SMAR). Description of the these models can be obtained from the Rainfall Runoff Library (RRL) link website https://wiki.ewater.org.au/display/SD41/ (accessed on 30 February 2020) of the "eWater toolkit" and the setup can be acquired freely online from https://toolkit.ewater.org.au/ (accessed on 30 February 2020). Other models include; Stanford Watershed Model, MIKE11/SHE (Refsgaard & Storm, 1995); WATFLOOD and HEC-HMS (David Ford *et al.*, 2008), HEC-RAS, SWAT (Anorld et al; 2012), TOPMODEL (Beven et al., 1984; Beven & Kirkby, 1979).

Australian Water Balance Model (AWBM)

Australian Water Balance Model (AWBM) is a catchment water balance model used to compute runoff from rainfall at a daily or hourly time step (Boughton, 2004). It allows easy evaluation of different model types, support various time series input data formats, has the ability to display the wettest and driest years and also allow automatic setting of warm up periods. The main input data of Australian Water Balance Model are rainfall and evapotranspiration. It uses three surface stores to perform simulation of partial areas of runoff. Each of the three surface moisture stores are directly fed with rainfall and evapotranspiration is subtracted. Any excess flow from each surface store after meeting evapotranspiration demand, converts into runoff which is separated to become surface runoff or base flow. The generated surface runoff can be channelled through the routing store if necessary, to simulate the delay reaching the outlet of an average to huge catchment.

The water balance equation is;

$$store_n = store_n + rain - evap\left(n = 1\ to\ 3\right) \tag{2.1}$$

If the value of moisture in the store becomes negative, it is reset to zero, as the evapotranspiration demand is superior to the available moisture and when the value of moisture in the store exceeds the capacity of the store, the moisture in excess of the capacity becomes runoff and the store is reset to the capacity. Runoff occurring from any store can result into part of the runoff becoming recharge of the base flow store provided that there is base flow in the stream flow. Routing of surface runoff can be done through a store if needed to simulate the delay of surface runoff reaching the outlet of a medium to large catchment. Three partial areas (A1, A2, A3) and capacities (C1, C2, C3) offer enough flexibility to fit to rainfall and runoff data but the parameters are few enough to permit positive calibration. The surface attenuation store is used when the calculations are in daily time steps. Discharge from the store and that from the baseflow store is calculated as shown in Figure 1. Stream flow record can also be used to directly determine the baseflow recession constant. Base flow index (BFI) is the ratio of base flow to total flow in the stream flow.

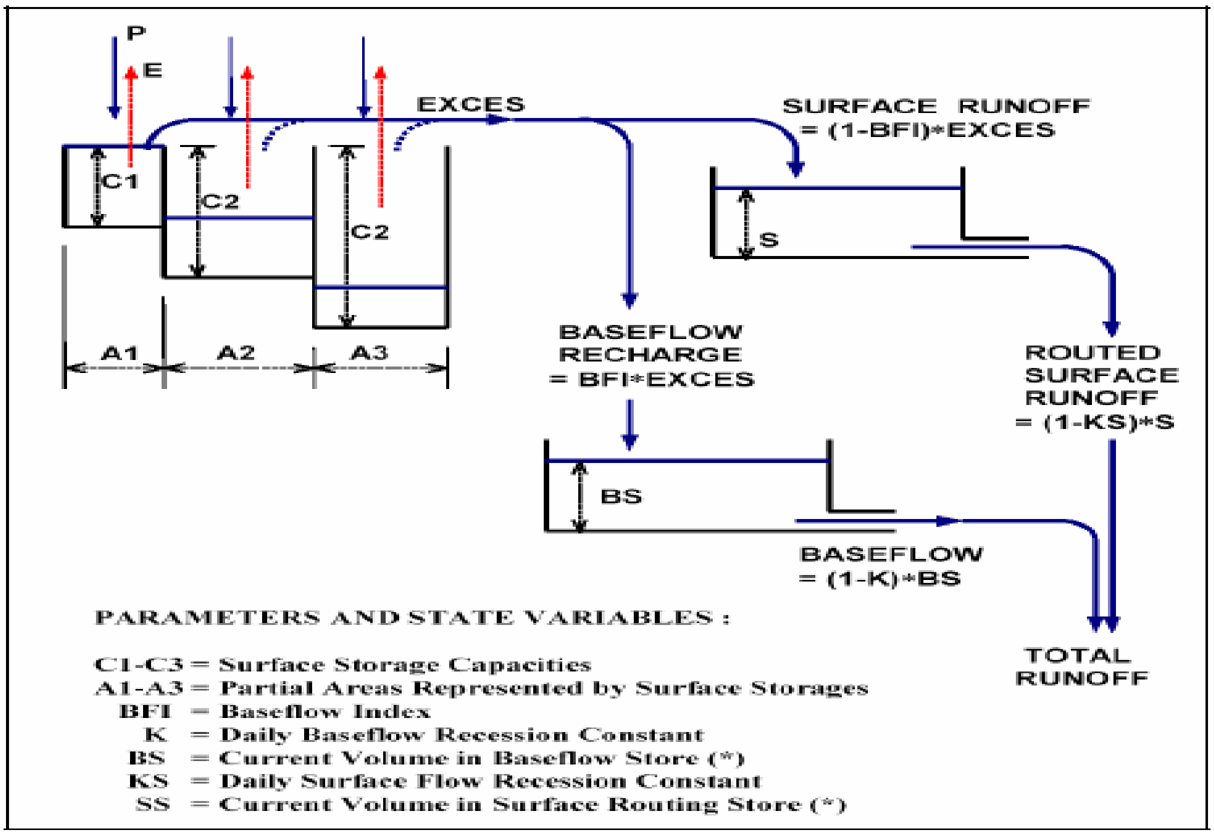


Figure 1. Structure of Australian Water Balance Model

Australian Water Balance Model (AWBM) is not any different from the rest of lumped conceptual hydrological models except that to apply it outside Australia, calibration and testing to site-specific catchments characteristics is necessary. Australian Water Balance Model (AWBM) has been applied in several catchments for example (Haque et al., 2015), (Ankit & Tiwari, 2015) in modelling monthly river flow of Bina basin in India and (Zhang et al., 2016) in modelling monthly streamflow in the Poyang Lake basin. Onyutha, (2016) applied it in the simulation of moderate and extreme flows on Blue Nile basin and was the best compared to other models (Tank, SAC, SIMHYD, SMAR) as it produced the highest Nash Sutcliff efficiency of 0.86 applied in the study. Onyutha, et al (2020) applied the model on River Kafu catchment in Uganda and the model yielded appealing results with Nash Sutcliff efficiency of 0.7 compared to other hydrological models.

2.5 Reservoir simulation models.

Reservoir models are mostly constructed from existing data which represents the physical configuration and measured data sets that represent transient operational, hydraulic, water quality conditions, and meteorological. Model selection usually depends on the time and funding available for, data collection, model calibration to a range of hydrologic conditions, running model simulations, and for result preparation and presentation.

Wurbs, (2005) listed the most popular simulation modelling soft-wares that have been used in several studies and the projects.

Table 1. List of most popular reservoir simulation models

Short name	Descriptive name	Model applications
RiverWare	River and Reservoir Operation	Reservoir system operation optimization and operational policy evaluation.
MODSIM	Generalized River Basin Network Flow Model	Simulating conservation operations.
MIKE BASIN	GIS-Based Decision Support for Water Planning &Management	Optimizing reservoir and hydropower operations.
WEAP	Water Evaluation and Planning	Maintaining water balance databases, generating water management scenarios and performing policy analyses.
HEC-ResSim	Reservoir System Simulation	Simulating conservation and flood control operations.

RiverWare: The model was developed in 1986 by the Centre for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado Boulder. It is a river-reservoir modelling platform which simulates reservoir and system operations, responsive forecasting, operational policy evaluation, system optimization, water accounting, and water rights administration (Zagona et al., 2001). The model relies on logic within rules that drive the simulation. The rules are complex algorithms that express variable operational policy that can be prioritized. According to Labadie (2006), RiverWare is customized using the RiverWare Policy Language (RPL) used for developing operational policies for river basin management and operations. A rule editor prompts users to enter logical expressions in RPL defining rules by which objects behave, as well as interrelationships between objects for simulating complex river basin operations. As an interpreted language, RPL is far less computationally efficient than compiled code. For priority-based water allocation in a river basin, extensive complex rule bases are required.

MODSIM: It is a Generalized River Basin Decision Support System (DDS) and network flow tool that performs integrated analysis of water sector elements and optimization of resource management through allocation of the scarce water resources (Berhe et al., 2013). With MODSIM, debugging problems can be difficult because no graphic user interface or debugging tool is provided to view the optimization of the network flow. Users are required to follow within the software's executed syntax and interpret it to identify bugs. Basing on this alone, MODSIM needs sufficient investment and due diligence by the user to learn. This is one of the reasons why most users do not apply this simulation model in their studies.

MIKEBASIN: It is a GIS based decision support for integrated water resources management and planning. It provides solutions and alternatives to water allocation and water shortage problems, improving and optimizing reservoir and hydropower operations, carrying out evaluation and improvement of irrigation performance, solving multi-criteria optimization problems, exploring conjunctive use of groundwater and surface water, and establishing cost-effective measures for water quality compliance. It simulates multiple-purpose and multiple-reservoir systems based on a network formulation of nodes and branches. Monthly time series of inflows to the stream system are provided as input parameters to the model. It contains various options for specifying reservoir operating rules and allocating water among various water users.

HEC-ResSim; is a modelling hydraulic software program, initiated by USACE HEC in 1996 but was first released to the public in 2003 with the intention of eventually replacing HEC-5, which has been extensively applied for over 30 years. HEC-ResSim is an original program, sharing no code with its predecessor in spite of it serving similar purposes to those of HEC-5. The model comprises of a graphical user interface, a computational program to simulate reservoir operations, data storage and management capabilities, graphics and reporting facilities. It is used in:

Planning studies for evaluating existing and proposed reservoirs, Planning reservoir operations, and flood risk management sizing and conservation storage requirements for various projects. The model simulates reservoir operations including all reservoir characteristics and channel routing downstream. It also allows users to define various alternatives and run simulations simultaneously to compare results (Klipsch & Hurst, 2013).

HEC-ResSim model has several capabilities that prompts its use mostly in reservoir operation studies and these include; the advanced features such as outlet prioritization, scripted state variables, and conditional logic makes it possible to model more complex systems and operational requirements.The network solution algorithm along with the iteration convergence sequence for return flows and watch logic inbuilt in the model, gives the model user flexibility to simulate operations of complex river systems. HEC-ResSim provides the spillway discharges in terms of gate opening through detailed representation of the gate management on the level of the individual gates (Uysal et al., 2016).

HEC-ResSim contains three separate modules which are; watershed, reservoir and simulation module. With the watershed setup module, the user builds stream alignments (Stream alignments then create stream elements, nodes, and junctions), diversions, draws the location of reservoirs, levees, diversions, and off storage areas, and set computation points. With the reservoir module, the user builds the network schematic, describe the physical and operations elements of the reservoir, add routing reaches and define alternative scenarios for analysis. The simulation module performs the configuration of the simulation and reviewing of results.

HEC-ResSim according to USACE (2007) is a generalized reservoir simulation system program which depends on the mass balance equation and reservoir systems are simulated using user defined zones, rules and IF-THEN-ELSE statements. Once the physical reservoir conditions are represented, the several different reservoir operation approaches can be generated and operated to achieve a guide curve for the target elevation. HEC-ResSim model uses an original rule-based approach to imitate the operational decision-making process that reservoir operators follow in setting reservoir release schedules. According to USACE (2007), the HEC-ResSim release decision-making process for a reservoir takes into account the time of the year, hydrologic conditions, temperature of the water, and simultaneous operations by other reservoirs in a system. HEC-ResSim when employed as a decision support tool meets the needs of modelers performing various reservoir project studies as well as meeting the needs of reservoir regulators during real-time events (U.S. Army Corps of Engineers (USACE), 1997).

Reservoir System Simulation in HEC-ResSim.

Evaluation of reservoir system operation under specified operation rules and set of input quantities is complex which requires detailed simulation of the operation over long periods of time. It is accomplished by assuming that steady-state conditions exist for successive intervals of time which must be short enough to capture the details that affect system outputs. For example, average monthly flows may be used for most conservation purposes unlike for hydropower reservoirs as it may not provide an accurate estimate of energy production.

According to U.S. Army Corps of Engineers (USACE) (1997), the simulation model solves the continuity equation with the reservoir release as the decision variable while analyzing the system in an upstream-to-downstream direction. At each appropriate location, requirements for each service are noted, and the reservoirs at and above that location are operated in a way to serve those requirements (like water demands), subject to reservoir system constraints which include outlet capacity, channel capacity, and reservoir storage capacity. The tentative release decisions made for upstream locations become increasingly constraining as the computation procedure proceeds to downstream locations of the reservoir system.

The mass balance equation for reservoir inflows, outflows, and changes in storage computation is given below.

$$S_{t+1} = S_t + I_{t} - E_t - R_t - S_{p\,t} \qquad (2.2)$$

Where t is period, S_t and S_{t+1} is the reservoir storage at the beginning and end of the period, I_t, E_t, R_t, and $S_{p\,t}$ are inflow to the reservoir, evaporation loss, release and spill during the period respectively.

According to Fagot et al (2011), HEC-ResSim data requirements include, the physical and operational characteristics of dam and reservoir. The physical reservoir data is expressed in the form of volume-area and elevation curves which include the type and capacity of each outlet. The operational data includes the zone definitions along with the rules governing the operations in each zone. The outputs are; graphs, reports and tables of reservoir operation simulations.

Many studies have been conducted with HEC-ResSim model and yielded appealing results. OLani, (2006) applied ResSim in Wadecha – Belbela reservoirs to investigate monthly maximum irrigation potential and establish water release guide rules to the irrigation schemes under inflow scenarios. Asefa, (2011) applied ResSim in water use and operation analysis of water resource Systems in Omo Gibe river basin. The model performed well in simulating the recent and proposed development interventions on water resource. Mariam, (2012) built a simulation model for Tekeze dam reservoir in Ethiopia, with a study aim of finding out the optimal operation policy for the production of hydroelectric power and for the fulfillment of the requirements at the downstream of the dam using HEC-ResSim 3.0 package.

3.0 MATERIALS AND METHODS

3.1 Description of the study area

Kabalega Hydroelectric Power Station, also known as Buseruka Power Station is a 9 MW (12,000 hp) mini hydroelectric power project located across River Wambabya, in Buseruka Sub County, Hoima District, in Western Uganda . River Wambabya catchment has a drainage basin area of 795 km^2 stretching from 1˚ 13' 36.6"- 1˚ 33' 33.6" N and 31˚ 3' 45"- 31˚ 24' 27.5" E with elevation ranges of 634 - 1441 m above mean sea level. The location coordinates of the reservoir centroid are 1˚ 32' 42" N, 31˚ 6' 41" E.

3.1.1 Rainfall

The area receives an annual average rainfall of 1,270 mm, with high variability, from approximately 800 mm over Eastern L. Albert parts to approximately 1,400 mm over the western parts. It receives two rainy seasons with the main season from August to November, peaks in October while the secondary season is from March to May with the peak in April. Main dry season is from December to about mid March. There is a secondary dry season from June to July (WWF, 2006).

3.1.2 Soils

The catchment is characterized with Ferralitic, ferrosols, and hydromorphic soils as the main types of soils found in the basin. They are yellowish-red clay loam soil on sedimentary bed (WWF, 2006). Soils on high land areas are lateritised, red clay loams (kitonya catena) derived from phyllites which provide medium to high productivity of crops like for coffee and maize.

3.1.3 Land use land cover

The vegetation of the area is broadly classified into forest, savannah, grassland and swamps. The vegetation provides water catchments, food and climate modification due to its biodiversity (Plumptre et al., 2003). The natural forests have over time been degraded due to pressure on land. Human activities such as deforestation, wetland degradation have had a great influence on the natural vegetation in the catchment (Masindi District Environment Department, 2005). Timber cutting and selling has become a lucrative business in the region and many people are engaged in the lumbering activity. This is to provide land for crop cultivation, settlement and livestock rearing which are dominant economic activities in the catchment area.

3.1.4 Water resource

The inflows into Wambabya River is from Rwamutonga River and Nyamanga River which originate from the areas of Hoima and Kiziranfumbi respectively. The lateral inflows into the river from the escarpments are seasonal and contribute very little, since the catchment is small. The normal annual land runoff contribution of the catchment to lake albert basin is 11.3% (WWF, 2006).

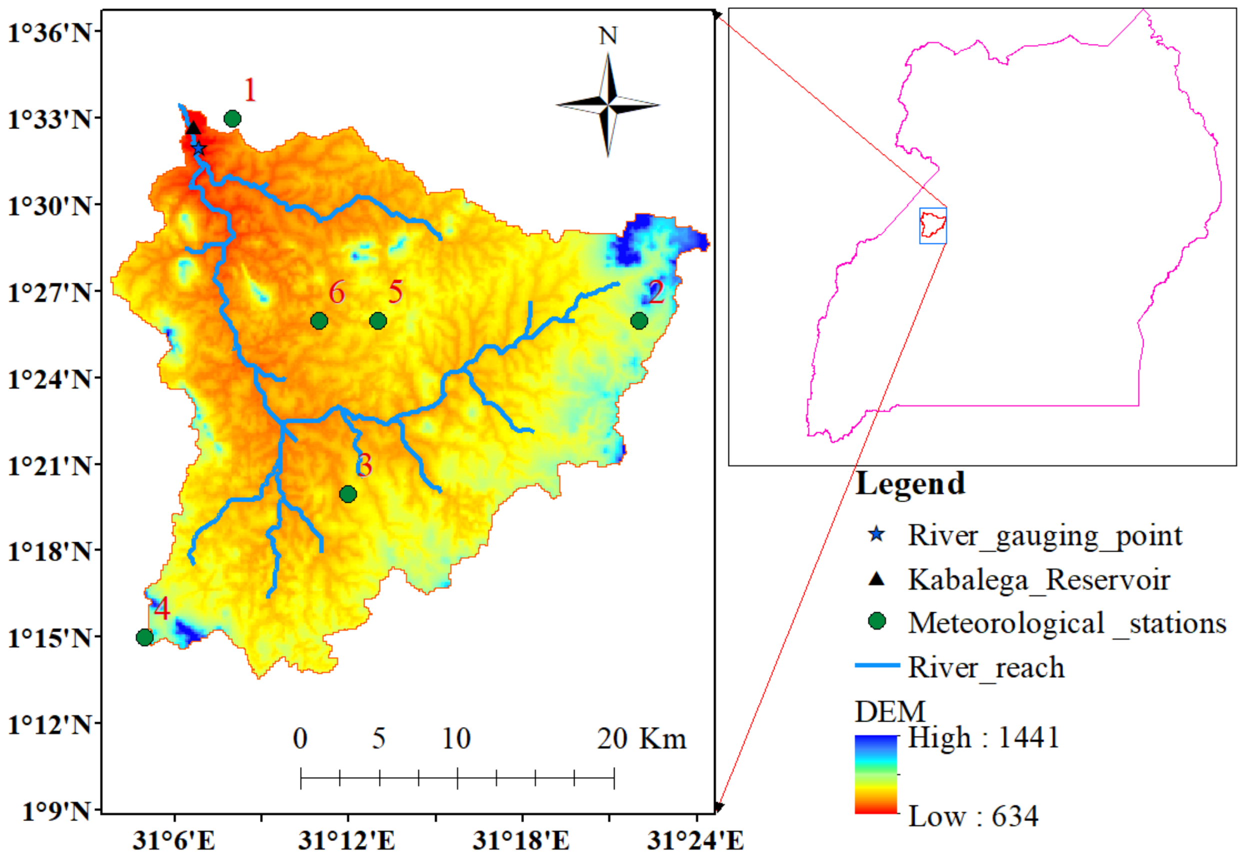


Figure 2. Location map of Kabalega Reservoir in Wambabya River Basin

3.2 Data collection, preparation and analysis

3.2.1 Climate Data:

The time series climate data comprising of rainfall, maximum and minimum temperature of the following meteorological weather stations in Table 2 for a period from 1990-2019 were obtained from Uganda National Meteorological Authority (UNMA). The station numbers in Table 2 correspond to meteorological stations as shown in Figure 1.

Table 2. Meteorological stations within the catchment.

Station Numb.	**Station name**	**Latitude**	**Longitude**	**Elevation(m)**	**Percentage of missing data**
1	Buseruka	1.55	31.13	610.00	5.60
2	Hoima	1.45	31.45	1158.00	9.58
3	Kiziranfumbi	1.33	31.20	1100.00	11.50
4	Kabwoya	1.25	31.08	880.00	11.38
5	Bugambe Tea Estate	1.43	31.22	1096.00	9.76
6	Rwabikondo	1.41	31.18	1067.00	12.33

The Potential evapotranspiration (PET) (mm/day) was computed using the equation Eq 3.1 (Hargreaves & Allen, 2003). The method requires mainly minimum and maximum temperatures as the key inputs. This simplified PET estimation method was chosen instead of the Food and Agricultural Organization of the United Nations (FAO), Penman- Monteith method (Allen et al., 2006) due to the limited or inadequate meteorological data which include solar radiation, relative humidity and wind speed for the catchment.

$$PET = 0.0023\left(T_{mean} + 17.8\right)\left(T_{\max} - T_{\min}\right)^{0.5} Ra \qquad (3.1)$$

$$Ra = \frac{24x60}{\pi} x \ 0.082 \ x \ d_r \ x\left[\left(\omega_s \ x \sin(\varphi) x \sin(\delta) + \cos(\varphi) x \cos(\delta) x \sin(\omega_s)\right)\right]$$

$$d_r = \left(1 + 0.033 \ x \ \cos\left(\frac{2\pi}{365} J\right)\right)$$

$$\omega_s = \arccos\left[-\tan\left(\varphi\right)\tan\left(\delta\right)\right]$$

$$\delta = 0.409x\sin\left(\frac{2\pi}{365}J - 1.39\right)$$

Where: R_a is the incoming extra-terrestrial radiation in mm/day. This was estimated based on the location's latitude φ and the calendar day of the year J. T_{mean}, $T_{\max}$ and $T_{\min}$ are the mean, maximum and minimum temperatures respectively.

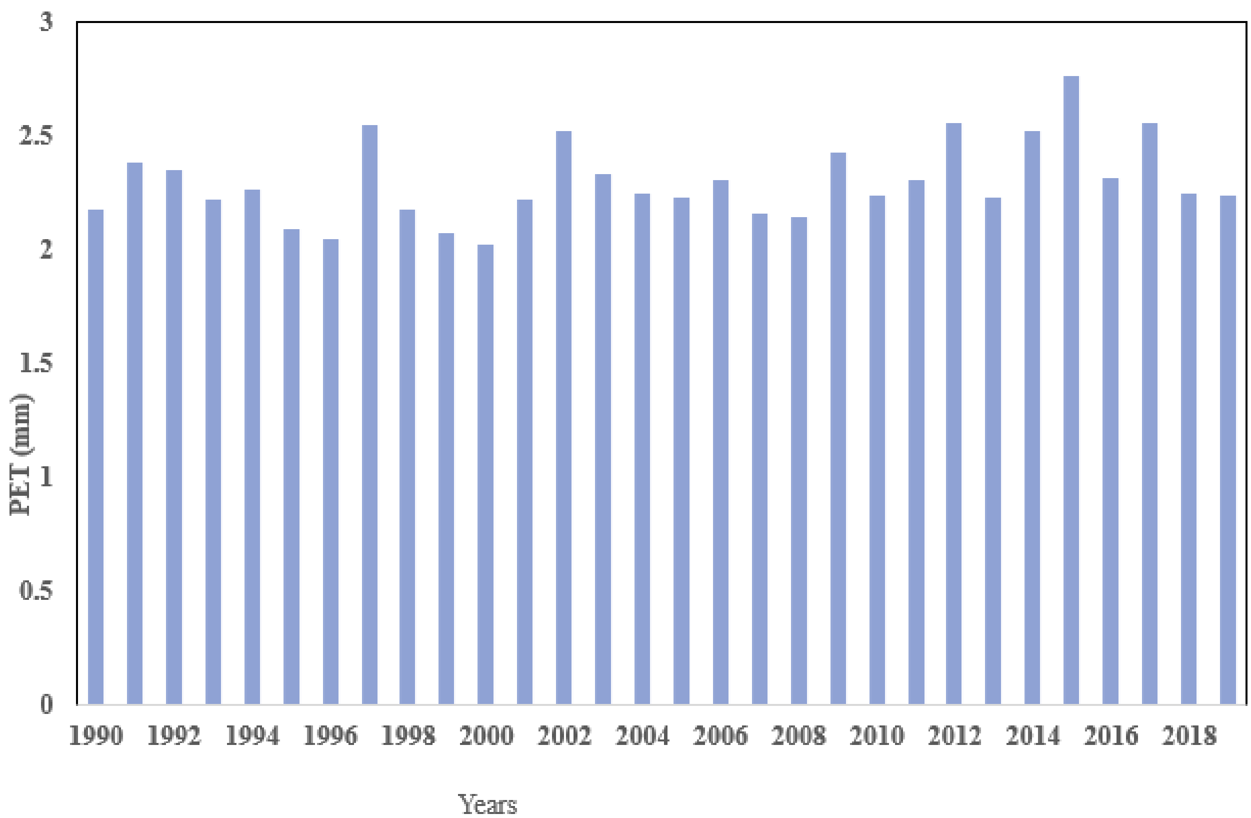


Figure 3. Mean annual potential evapotranspiration.

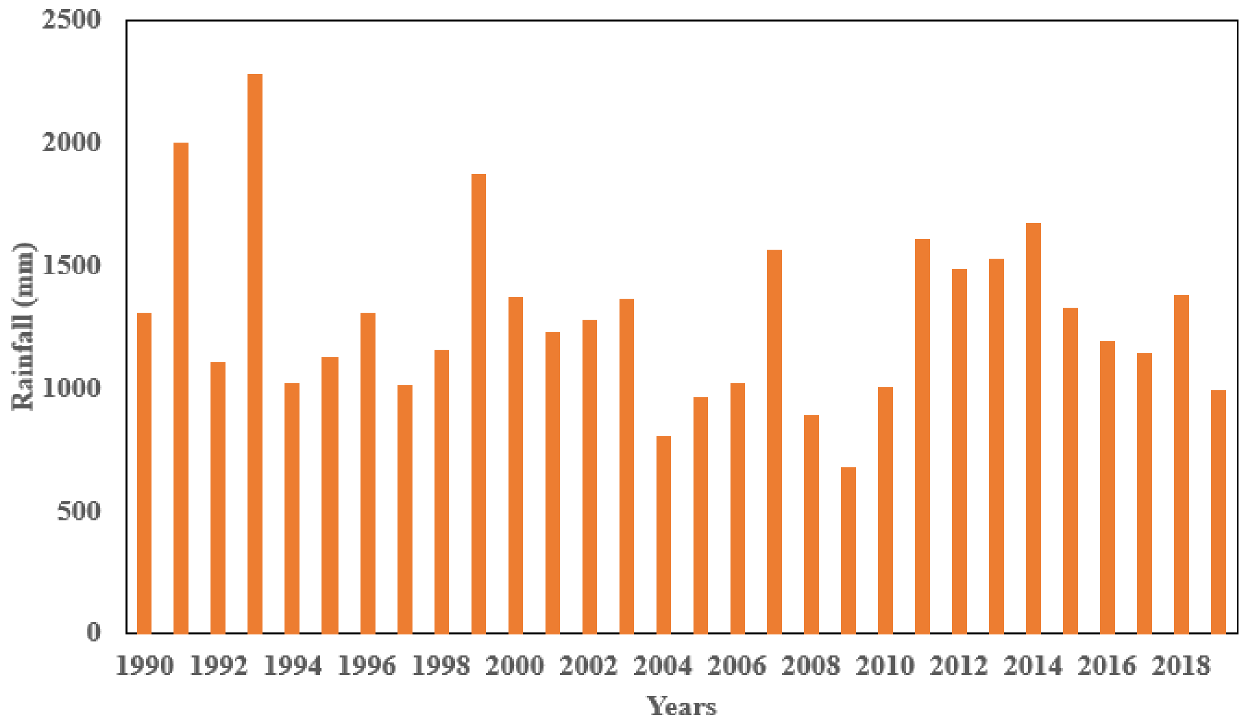


Figure 4. Annual rainfall at Buseruka station

Homogeneity test

Homogeneity test detects variability existing data. Data can be inhomogeneous when measurements of the data are not taken at a time with the same instruments and environments (Suhaila et al., 2008). This implies that a homogeneous climate series is one where variations are caused only by changes in weather and climate. Achieving homogeneity when dealing with rainfall data is usually a hard task because it is affected by changes in measurement techniques and observational procedures, environment characteristics and structures, and location of stations (Ho Ming & Fadhilah, 2012). These could affect the accuracy of the analyses and therefore, it is very crucial to derive a homogeneous time series before conducting any analysis involving rainfall data. Any inhomogeneous series must thus be detected, adjusted or removed from the analysis.

There exist a number of homogeneity tests used to test the homogeneity of the rainfall data and they include; Standard normal homogeneity test (SNHT), Buishand range (BR) test, Pettitt test, and von Neumann ratio (VNR) test. The annual values *Yi* of the testing variables *Y* under the null hypothesis, are independent and identically distributed and thus the series are considered as homogeneous. Standard normal homogeneity test (SNHT), Buishand range (BR) test and Pettitt test assume the series consist of break in the mean and consider it as inhomogeneous under alternative hypothesis. These tests are capable of detecting the year where break occurs except VNR test which is not able to give information on the year break since the test assumes that the series is not randomly distributed under the alternative hypothesis (Wijngaard et al., 2003).

The absolute tests are considered in this study because the rain gauge stations used are sparsely distributed. Each station thus has a different surrounding area and different climatic environment. Therefore, to construct a homogeneous reference series which has uniform climatic conditions over the region including the site whose data are being evaluated is quite impossible.

The standard normal homogeneity test, Pettit and Buishand range test were used to test the homogeneity of the rainfall data from the above meteorological stations. This is because there was need to check the breaks at the beginning, middle and near the end of the series. SNHT is sensitive in detecting the breaks near the beginning and the end of the series whereas Pettit and Buishand range detect breaks in the middle of the series. Annual mean was chosen for homogeneity testing because the daily rainfall series of the stations consisted of at most 10% missing values and these stations were selected (Ho Ming & Fadhilah, 2012).

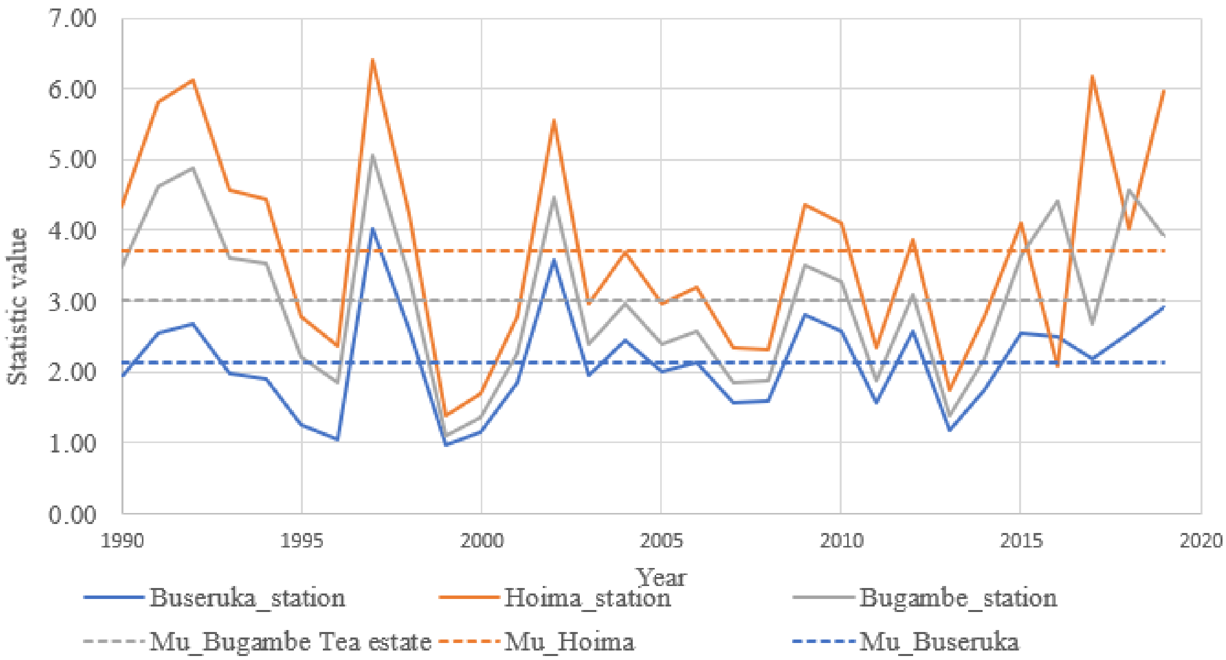


Figure 5. Homogeneity for Buseruka, Hoima and Bugambe Tea estate station

The above homogeneity graphs for the above stations show that the data is homogeneous, and thus worthy being used for rainfall analysis.

Filling missing rainfall data

Different techniques for filling missing rainfall data gap exist. These include the normal ratio, comparison and Inverse Distance Weighted interpolation technique. The comparison method considers the mean annual rainfall of station with missing data with that of an adjoining station thus too shallow whereas normal ratio needs when adjoining index stations are evenly distributed. Since the stations in the study area were not evenly distributed and since also concurrent data existed in the surrounding stations, missing values in the observed rainfall data were infilled using the Inverse Distance Weighted (IDW) interpolation technique developed by Shepard (1968) Eq. 3.2. Because of the robustness of IDW, the technique has been applied in a number of studies (Mubialiwo et al., 2020; Chen et al., 2017; Das, 2019; Lam et al., 2015; Charles Onyutha, 2017; Pellicone et al., 2018). The missing rainfall depth or intensity R_m at station m for a particular period was obtained using rainfall values R_p of the neighbouring stations q of the same particular period.

The following equation shows the Inverse Distance Square Approach.

$$R_M = \sum_{p=1}^{N} R_p \times d_p^{-\tau} \left(\sum_{p=1}^{N} d_p^{-\tau} \right)^{-1} \tag{3.2}$$

Where; d_p is the distance between station m with missing data record and the neighbouring station N being used for interpolation. τ is the power parameter which determines the dependability of the Inverse Distance Weighted interpolations. A small value of τ yields in an average value when all the neighbouring stations are considered whereas a large value of τ is yielded when only the nearest neighbouring stations is considered and ignoring input from the other distant neighbouring stations (Lu & Wong, 2008; Pellicone et al., 2018). In order for the interpolation errors to be minimised, a value of τ =2 is recommended for either daily or monthly data, τ =3 for hourly and τ =1 for annual data. Basing on the recommendation by (Goovaerts, 2000) and (Lloyd, 2005), a value of τ =2 was applied for this study.

Checking for consistency of rainfall data records

From several years' records it may seem that annual rainfall is, say, declining. It is important to know that this trend is independent of the gauging, and is due to meteorological conditions only.

This may be checked by plotting a double mass curve. This technique is based on the principle that when each recorded data comes from the same parent population, they are consistent (Rugumayo, 2012). The precipitation values at station X beyond the period of change of regime are corrected by using the relation:

$$P_{cx} = P_x \frac{M_c}{M_a} \quad (3.3)$$

where; P_{cx} corrected precipitation at any time $t_1$at station x.

P_x = original recorded precipitation at any time $t_1$at station x.

M_c= corrected Slope of double mass curve.

M_a= original Slope of the double mass curve.

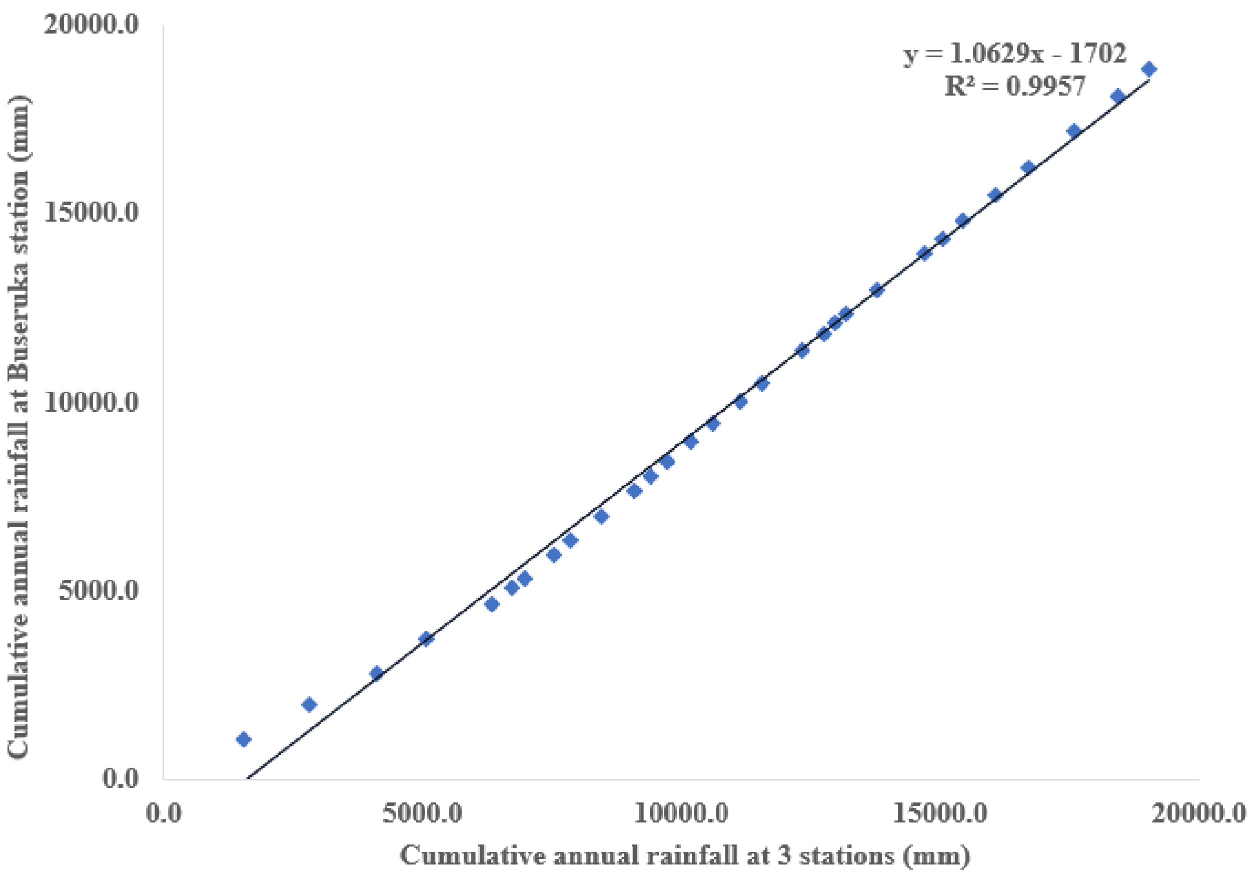


Figure 6. Double mass Curve of Buseruka with Hoima, Bugambe and Kiziranfumbi station

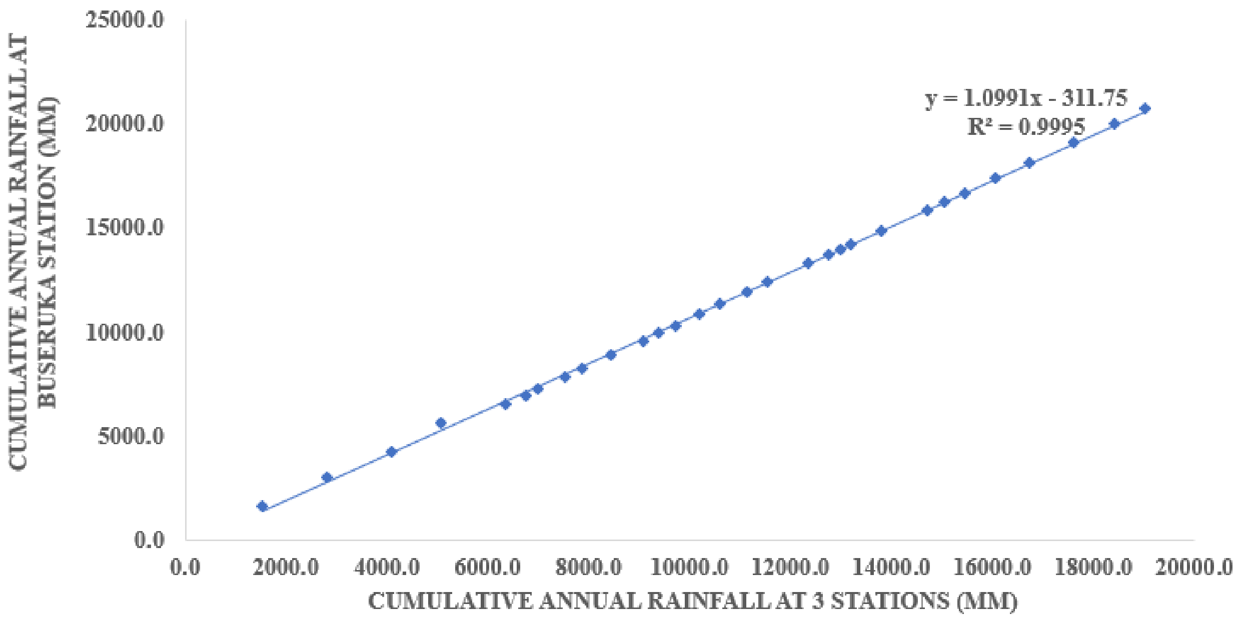


Figure 7. Adjusted double mass curve of Buseruka with Hoima, Bugambe and Kiziranfumbi station.

Areal rainfall (mean basin precipitation)

Estimation of the areal rainfall over a given catchment is useful for estimating the total response (runoff) generated from the entire catchment or to estimate the intervening catchment runoff response that is generated between the observation station and the dam site. Various methods can be implemented to estimate the areal rainfall amount in the intervening catchment but the most famous method is the Thiessen polygon method (Thiessen, 1911) where by the influence of each rainfall station is determined and the weighted average rainfall estimated.

To determine the areal rainfall in Wambabya catchment, Theisen polygons were constructed using Arc-GIS software. The weighting factor for each gauge reading is a function of the polygon area surrounding the rain gauges of which this area is expressed as a percentage of the total area of the basin. The weighted precipitation for each station (Pw) was computed by multiplying the precipitation at each station by the weighted area and summing them up to give the basin precipitation. With this method, the rain gauge stations outside the catchment are used effectively.

$$\overline{P} = \sum_{i=1}^{M} P_i \frac{A_i}{A} \tag{3.4}$$

where $\frac{A_i}{A}$ is weightage factor for each station.

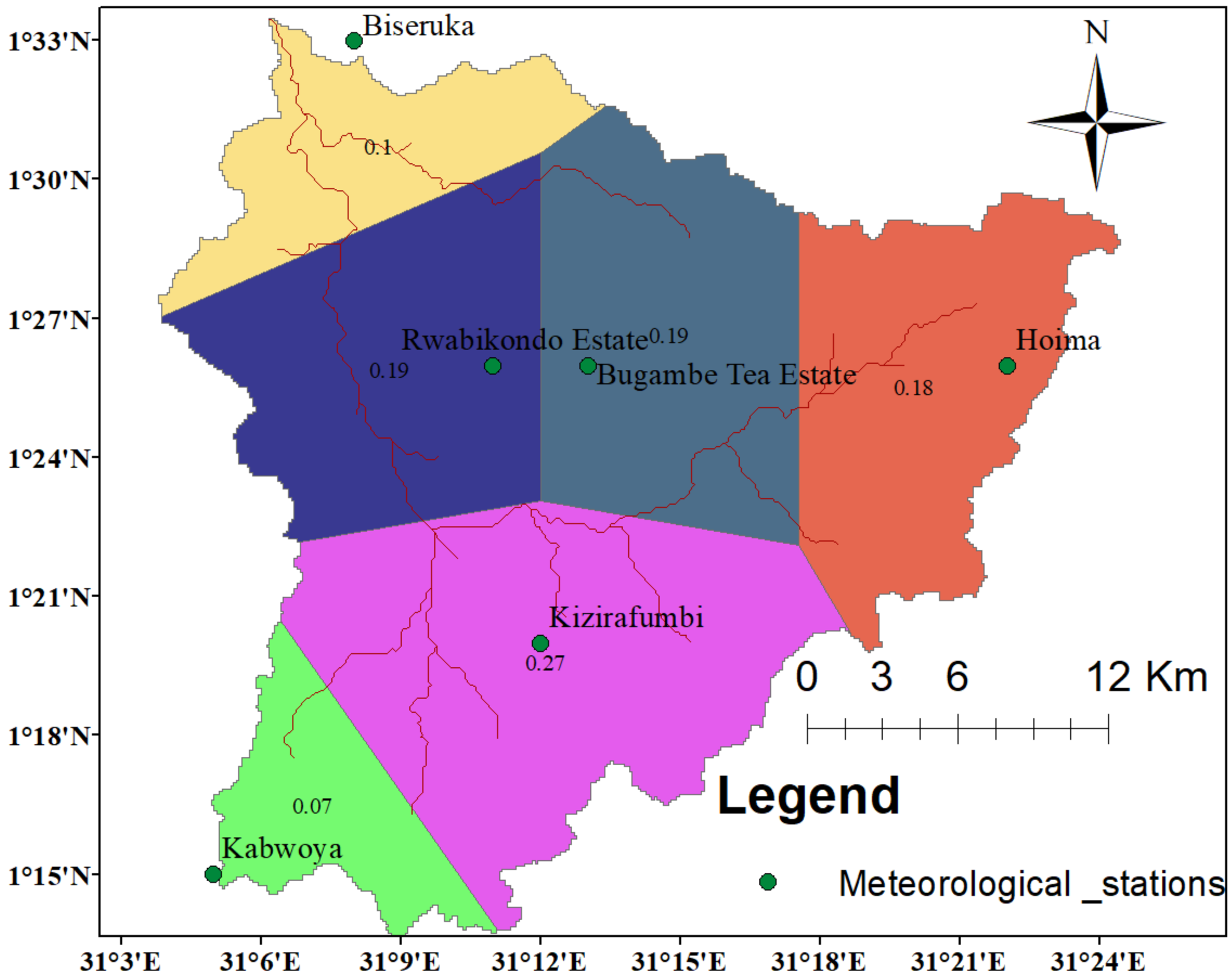
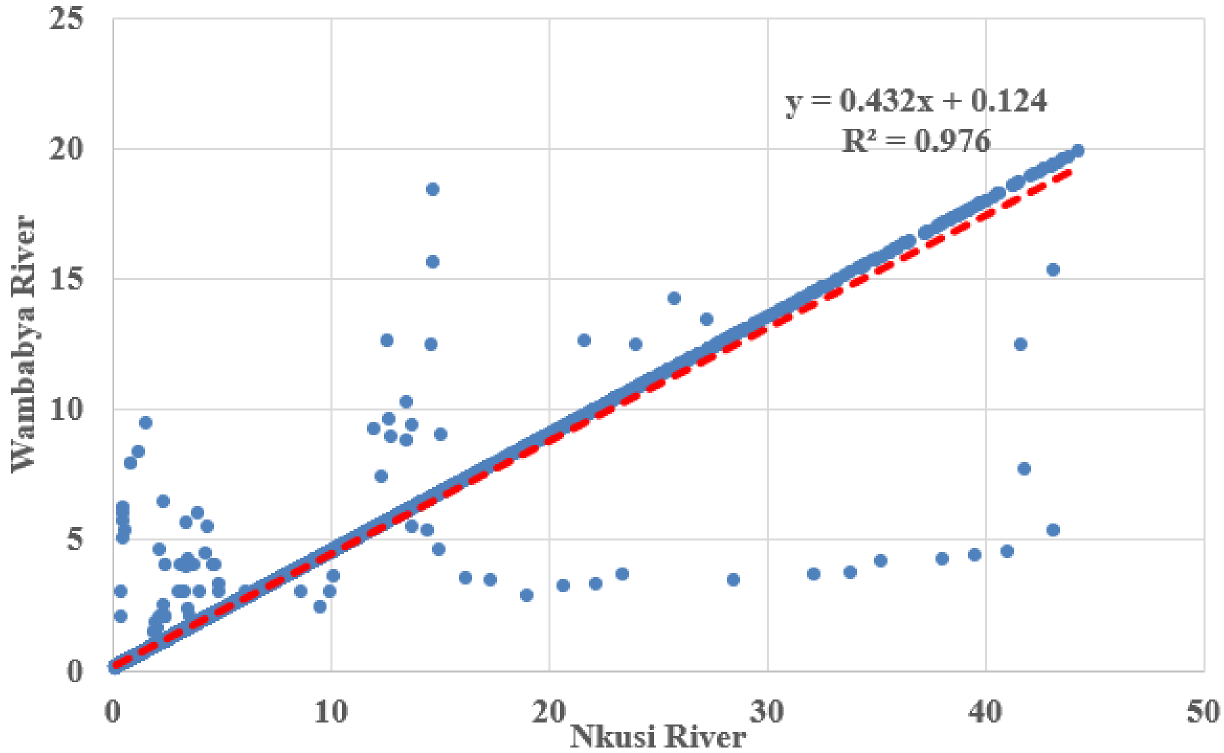


Figure 8. Thiessen polygons for meteorological stations in Wambabya River catchment.

3.2.2 Hydrological Data.

The daily stream flow data at the gauged point of River Wambabya for a record of 1990-2019 was obtained from Uganda Ministry of Water and Environment, Directorate of Water Resources. Linear regression analysis techniques were employed in filling the missing stream flow data which was found to have some missing data. An equation was developed considering the flows of Wambabya River and Nkusi River.

Linear regression analysis was considered for this study because Nkusi River flows showed a good linear relationship with Wambabya River flows in the slope and the intercept. Additionally, other river flow data of Rwamutonga and Nyamanga Rivers had short records with 15% missing data.



3.2.3 Reservoir system data.

Reservoir system data comprises of physical and operational reservoir data such as reservoir pool definition (elevation-area-storage tables), outlet capacity curves, hydro power plant data (outflow and generation capacities, efficiency, losses), operational zones, minimum and maximum release requirements.

Table 3. Dam physical data

Dam properties	Description
Length of the dam (m)	132.00
Spillway length (m)	25.00
Maximum height of the dam (m)	13.66
Spillway discharge capacity (cum/sec)	120.00
Reservoir capacity (m^3)	153000.00
Spillway elevation (m)	960.00
Top elevation of the dam (m)	961.50
Intake gate sill level of opening (m)	954.15
Environmental sluice gate level opening (m)	952.00

Reservoir losses

Reservoir water losses mainly include seepage and evaporation loss. Only evaporation loss was considered here due to the absence of seepage loss for the study. The contribution of the groundwater into the reservoir also counterparts the seepage flow loss in the reservoir.

Environmental releases

Environmental release is the amount of water allocated from the conservation section of the reservoir for down stream users and to maintain the morphology of the river route. This is incorporated with its own independent outlet structure which will be operational whether no water spills over the spillway or not. This demand particularly should be given due consideration especially for irrigation dams and hydropower dams for which the tail race is far from the dam. Fixing the numeric value of the discharge required, needs detail Environmental impact analysis for the project, which is not available for most of the projects. For some of the projects this demand has been given as percentage of monthly average inflow to the reservoir but for Kabalega dam, a constant value of 0.22 m^3/s was considered. This amount basing on the hydrological criterion for determining minimum environment flow requirement corresponds to a minimum flow of 10% of the annual average flow.

3.3 Simulation methods

3.3.1 Australian Water Balance Model (AWBM)

In this study, Australian Water Balance Model (AWBM) was used to simulate the runoff inflow into Wambabya River. This was done by undergoing through the following steps.

The rainfall runoff model library of the AWBM was set up to carry out rainfall runoff modelling for Wambabya River catchment of 795 km^2. The input data was catchment-averaged daily rainfall and daily evapotranspiration for a period of 30 years (1^{st} January 1990 - 31^{st} December 2019). These inputs were fed into the AWBM for simulation of Wambabya River inflow. Periods of warm up, calibration and validation were entered. Observed river flow data for the same period as the above inputs was used for calibration and verification of the Australian Water Balance Model.

Sensitivity Analysis

Sensitivity analysis helps to determine the sensitivity of model parameters by comparing the output variance due to input variability. The selection of influential parameters for a model calibration is based on sensitivity analysis as it shows parameters with high sensitivity to the output. It also evaluates the model capacity and helps to understand the behaviour of the system being modelled. Model parameter optimization is an important task in order to achieve a well representative hydrological model as parameters affect the complexity of hydrological modeling.

Sensitivity analysis was performed to determine the influence of a set parameters on predicting Wambabya River flow. The analysis was carried out on the eight parameters of AWBM to identify hydrologic sensitive parameters by comparing their relative sensitiveness. The most sensitive ones were chosen for calibration processes. The most sensitive parameters were surface recession constant, Baseflow index and the Baseflow recession constant.

The parameters were adjusted within the range of their minimum and maximum default limits until there was a perfect fit of the observed and simulated flow.

Table 4 Optimized parameters for Australian Water Balance Model (AWBM)

Parameter	value
Partial area (A1)	0.465
Partial area (A2)	0.485
Base Flow Index (BF1)	0.89
Capacities (C1)	0
Capacities (C2)	0
Capacities (C3)	465
Baseflow recession constant (K Base)	1
Surface recession constant (K Surf)	0.785

Model calibration and validation.

Calibration is a process to standardize estimated or simulated parameters by using deviations from observed values for a particular basin. It thus helps in deriving correction factors which can be applied to generate predicted values. Model validation verifies the robustness and ability of the model to describe the catchment's hydrological response, and additionally detect any biases that may be present in the calibrated parameters (Gupta et al., 2005). The performance of a model is usually better in calibration than in validation period, a circumstance referred to model divergence (Sorooshian & Gupta, 1995).

The model was first run in generic mode using shuffled complex evolution (SCE-UA), Rosenbrock method and then later optimized (model parameters) manually to obtain best set of model parameter simulating runoff with a high accuracy. The calibration period was from 1st January 1990 to 31st December 2009 with a warm up period from 1st January1990 - 31st December 1991. The validation of the model was done with the flows from period 1st January 2010 – 31st December 2019. Observed river flow data was used for model calibration and checking. Shuffled Complex Evolution was used as it has proven to be robust, effective, and efficient (in search of the parameter space) for a broad class of problems and has been applied for automatic rainfall-runoff calibrations (Charles Onyutha, 2016). SCE-UA method combines the strength of the simplex method with the concept of controlled random search, competitive evolution and the strategy of complex shuffling (Duan et al., 1993).

Accuracy of the model was examined on the basis of Coefficient of Determination (R^2) (Biondi et al., 2012), Nash Sutcliff efficiency (Sutcliffe & Nash, 1970) and Root Mean Square Error (RMSE) for both calibration and validation period. The NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. RMSE describes the difference between model simulations and observations in the units of the variable. Its value close to zero indicate perfect fit, however, values less than half of the standard deviations of the observations may be considered low (Singh et al., 2004).

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(o_i - e_i\right)^2}{\sum_{i=1}^{n}\left(o_i - \overline{o}\right)^2} \tag{3.5}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(e_i - \overline{e}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 . \sum_{i=1}^{n}\left(e_i - \overline{e}\right)^2} \tag{3.6}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{1}{2} (O_i - e_i)^2} \quad (3.7)$$

Where, O_i is observed flow, e_i is simulated flow, $\bar{o}$ is average of observed flow and $\bar{e}$ is the average of simulated flow and n is the number of data points.

3.3.2 HEC-ResSim model

HEC-ResSim model as a generalized reservoir simulation system program was used in developing reservoir operation policies for Kabalega reservoir. The steps involved gathering and analyzing data required for routing river flow (into the reservoir) and reservoir modelling, developing a model schematic that identifies the key locations in the watershed. Defining the physical and operational data for the reservoir and its components in the basin, flow routing in the main channel and calibration and verification of the model. These were done in watershed module, reservoir network and simulation module as below.

Watershed module setup

In HEC-ResSim, a watershed is a collection of data associated with a particular reservoir system. model schematic that identifies the key locations in the watershed are developed in this module. Here first the shape file of Wambabya River basin stream network which was obtained through delineation using Arc-SWAT an Arc-GIS extension was imported and used as a background map for tracing the main stream and main tributaries of River Wambabya. Stream alignments, nodes, junctions and location of reservoirs were built here, and setting of computation points.

Reservoir network module

A reservoir network module is used for editing element (reservoir, computation points and routing reach), placing additional elements on stream alignment and data which includes Physical and operational reservoir data that is; reservoir pool definition (elevation-area-storage tables), outlet capacity curves, hydro power plant data (outflow & generation capacities, efficiency, losses, etc), operational zones, minimum and maximum release requirements. Flow hydrographs from Australian Water Balance model were inputs to the ResSim model. The stream flow records were archived into the HEC-Data Storage System Visual Utility Engine (HEC-DSSVue). The HEC-DSSVue is a graphical user interface database system that allows efficient storage and retrieval of sequential data, such as times series records and other data types used in water resources management (CEIWR-HEC, 2009). The program software packages offer convenient editing, copying, and visual display of data via tables and plots, in addition to having various mathematical, basic hydrologic and statistical functions. A HEC-DSSVue database file containing daily discharge records was produced.

Muskingum-Cunge Prismatic Channel routing technique was used to route stream flow. This routing technique was chosen because the channel slope is less than 2 feet/ mile and does not require observed data unlike other methods like modified plus which require storage, outflow and elevation data. (Hydrologic Engineering Centre, 2007). River cross-sections at upstream of the reservoir were measured at several locations and the mean river dimensions computed and used in routing Wambabya stream flow from the upstream gauging point to the reservoir. These river cross-sections are inputs to the Muskingum Cunge prismatic channel routing technique.

An alternative consists of reservoir network, run control specifications, an operation set for each reservoir in the network, a storage balance operation set for each reservoir system in the network (if applicable), a definition of the initial (look back period) condition and mapping of all timeseries to identified local inflows is set from this reservoir module. Each alternative can be chosen in advance and compared with each other in simulation module. Time series data defined as DSSVue (Visual Utility Engine) files are imported into the alternative.

A reservoir is the most complex element of the reservoir network that is composed of a pool and a dam. HEC-ResSim assumes that the pool is level (that is, it has no routing behaviour) and its hydraulic behaviour is partly defined by an elevation-storage-area table. The pool is expressed by the reservoir's elevation-storage-area relationship which can include evaporation and seepage losses if need be. Criteria for reservoir release decisions, called an operation set, are based on specified storage zones that divide the pool by elevation and a set of rules that specify the goals and constraints governing releases when the storage level falls within each zone. The dam represents both an uncontrolled outlet and an outlet group, the top of dam elevation and length specifies the minimum parameters for an uncontrolled spillway (Wurbs, 2005). An operation set consists of three basic features: zones, rules and the identification of the Guide Curve. Decision logic of the program is related with zones, rules and guide curve. Zones are operational subdivisions of the reservoir pool. Each zone is defined by a curve describing the top of the zone.

Rules represent the goal and constraints upon the releases and Guide Curve is the target elevation of a reservoir.

Decision logic in HEC-ResSim

The basic decision logic for storage or release of water is based on the Guide Curve that describes the target elevation. Primarily, the physical data which includes both the reservoir and outlet works narrow the allowable domain. Secondly; rules and IF-THEN-ELSE statements restrict this domain and then finally the release or storage decisions are made with respect to guide curve regarding mutual rule restrictions. The rule limit is only effective since the amount of water will be released within the guide curve range. On the other hand, ResSim provides "specified rule types" which eliminates Guide Curve and release the desired amount of water although the target elevation is not achieved.

ResSim model can also perform in absence of the rules. When the pool level is below top of conservation (TOC), inflow will be held to allow the pool to rise, so the only constraint on getting the pool to the top of conservation is the inflow. If the pool is above the top of conservation, HEC-ResSim will release inflow and stored water to get back to top of conservation. The only constraint is the physical release capacity of the dam (Lara et al., 2014).

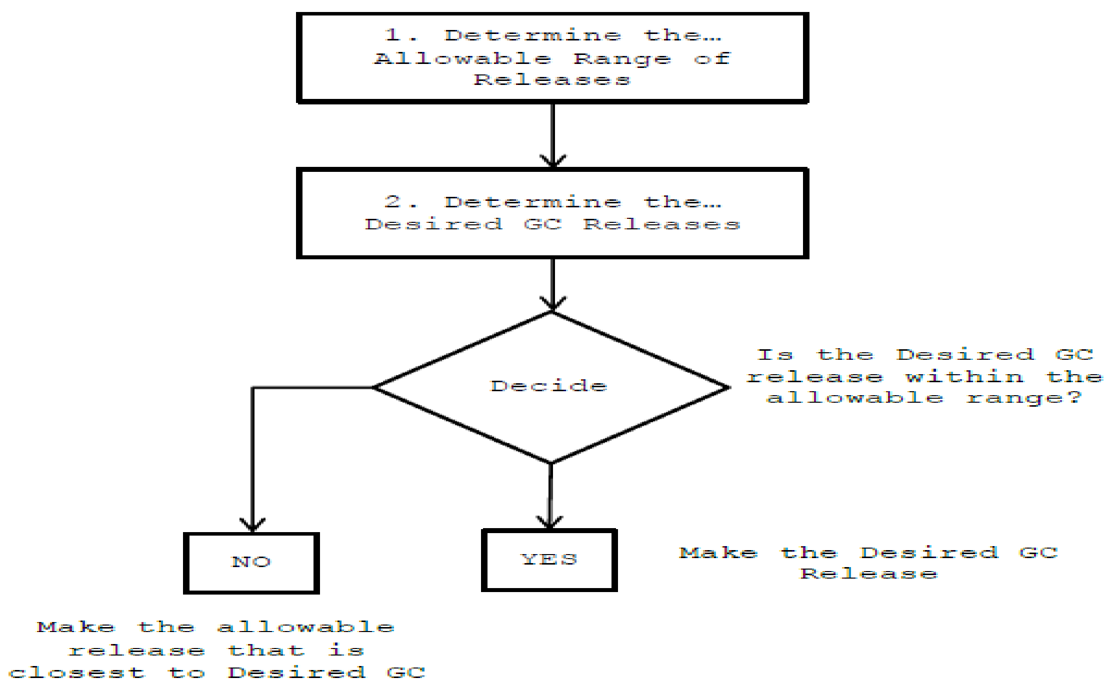


Figure 9. HEC-ResSim Basic decision logic (modified from Klipsch 2007)

Spillways are structures constructed to provide safe release of flood water past a dam to the downstream of a river. Spillways can be connected to an embankment dam or be part of a concrete as it is the case in Kabalega dam. For a given inflow flood hydrograph, the maximum rise of the reservoir level depends on the discharge characteristics of the spillway crest and its size which can be obtained by flood routing. Operating rules counteracting floods make use of the spillway's capacity to define water release quantity with different elevations. Spillway details for Kabalega dam are shown in Table 3.

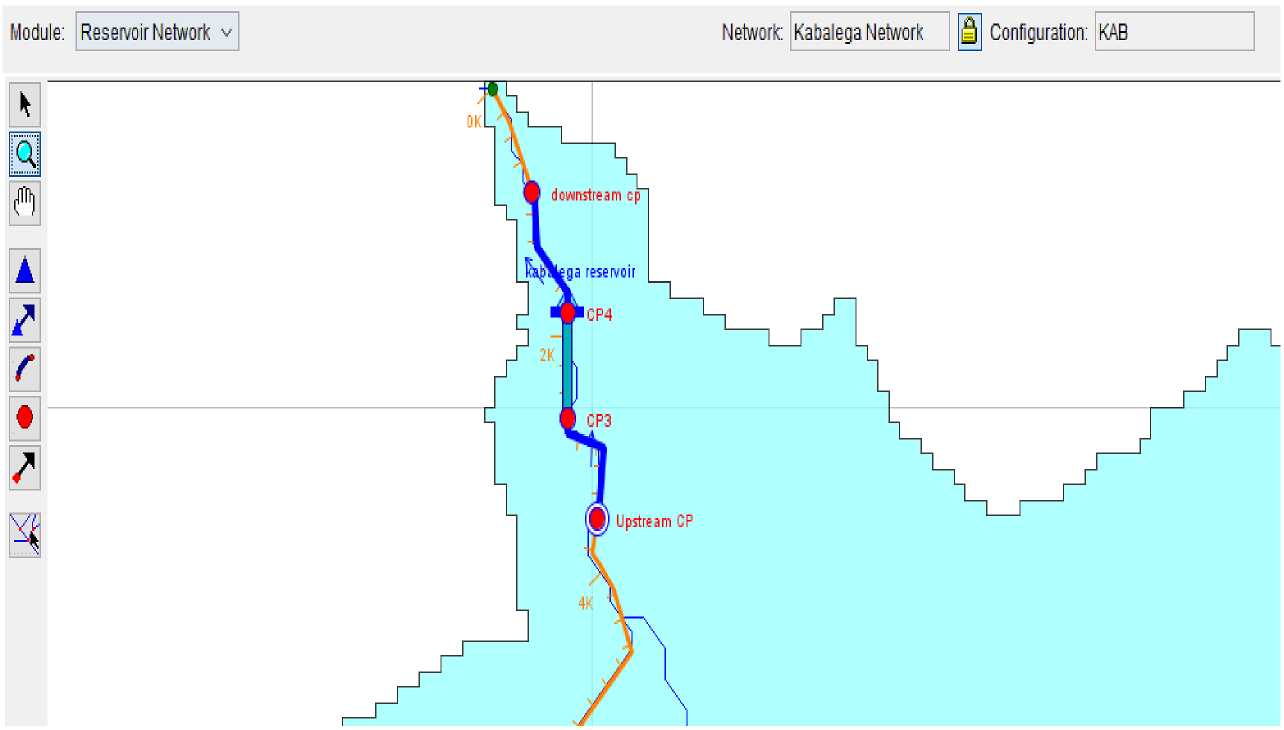


Figure 10. HEC-ResSim schematic model of Kabalega reservoir

Simulation module

The purpose of the Simulation module is to separate output analysis from the model development process. The time window and time interval parameters for either a single or a group of alternatives are specified here. The simulation module configures the simulation and then reviews results. Here the user has many ways to view model output. This can be accomplished by clicking on displayed objects, using HEC-DSSVUE, or utilizing a user created visual interface. Scripts developed in this module and packaged in a GUI can be used to post-process model output and create custom plots.

Calibration and verification of the model

Simulation was done basing on the current reservoir operating policies. A trial simulation was created and adjustments to the operating rules was made to ensure that the reservoir stores enough water to cater for periods of low flows while considering the physical dam constraints and minimum environmental flow requirements. The model was calibrated with observed flows measured at the downstream of the reservoir for period from 1st January 2012 – 31st December 2016. Model verification/validation was carried out for the period of 1st January 2017- 31st December 2019.

The model performance was measured by the convergence of simulated values to the observed values using statistical indicators that's Coefficient of Determination, Root mean square error and Nash & Sutcliffe efficiency. Graphical timeseries plots showing the fit between daily observed and simulated stream flows were also used.

3.4 Performance Criteria for Reservoir System

Quantitative measures of reservoir system performance used in modelling and analysis are usually formulated within the framework of the hierarchy of goals and objectives of the reservoir. These performance measures which are usually functions of the storage and release parameters to define an operating policy, quantitatively compare, for alternative operating policies, the effectiveness of the reservoir system in meeting target demands (Wurbs, 1991).

Reservoir performance evaluation criteria has been studied by several authors, Hashimoto et al., (1982) discussed three criteria which are; reliability, resilience, and vulnerability. Burn et al., (1991) formulated reliability, resilience and vulnerability criteria as risk-based performance measures for evaluating a real-time reservoir operation model. Loucks, (1997) introduced a measurement of the relative sustainability of renewable water resource systems. This study employed the following performance measures in analyzing the reservoir system operation policy.

Reliability

Reliability is the probability that a reservoir will be able to meet the target demand in any given period.

$$\mathrm{Re}\,liability = \frac{Nunber\ of\ \ times\ deficit\ Dt = 0}{Number\ of\ \ simulations} \quad (3.8)$$

Reliability is sometimes considered to be the opposite of risk, i.e. the risk or probability of failure is one minus the reliability α. There are several measures of reliability, discussed below.

Time-based reliability

It is the fraction of intervals during the simulation period in which the reservoir can meet the target demand, which can be expressed as

$$\mathrm{Re}\,l_t = \frac{N_s}{N} \qquad 0 \le \mathrm{Re}\,l_t \le 1 \tag{3.9}$$

where, Rel_t = time-based reliability, Ns = number of intervals that the target demand was fully met, N = total number of intervals covering the historical or simulation analysis period.

Occurrence-based reliability

Occurrence-based probability measures the annual time-based reliability, which represents the average probability of meeting the target draft in any particular year. Also, the annual time-based reliability will always be less than the monthly time-based reliability except when the reservoir has failed in each of the 12 months in a hydrological year.

Volumetric reliability

Volumetric reliability is defined as the percentage volume of the total demand that is released from the reservoir during the simulation period.

$$\mathrm{Re}\,l_v = \frac{\sum_{t=1}^{T} R_t}{\sum_{t=1}^{T} D_t} \qquad 0 \le \mathrm{Re}\,l_v \le 1 \tag{3.10}$$

Where;

R_t = water released from the reservoir in time period t, D_t = total demand in time period t, T = total simulating time period.

Resilience is the probability that once the system is in a period of deficit, the next period is not a deficit. Loucks, (1997) defined it as the probability that a satisfactory state follows an unsatisfactory state. A resilience index closest to 1 show that the system will return to the satisfactory state quickly and vice versa.

$$\text{Re}\,silience = \frac{Number\ of\ times\ deficit\ Dt\ =\ 0\ follows\ Dt > 0}{Number\ of\ times\ Dt > 0\ occured} \qquad (3.11)$$

Kjeldsen & Rosbjerg, (2001) stated that the resilience is equal to the inverse of the mean value of the time, the system spends in an unsatisfactory state.

$$\text{Re}\,s_{mean} = \left\{ \frac{1}{M} \sum_{j=1}^{M} d_j \right\}^{-1} \qquad (3.12)$$

where, dj = duration of the failure event, M = number of failure events.

Vulnerability: it is a measure of the likely damage of a failure event. A high value of vulnerability means the extent of damage due to failure is severe and vice versa.

$$Vu\ln erability = \sum_{D\,t\,>\,0} \frac{Deficit\ \text{D t}}{Number\ \text{of times D t} > 0} \qquad (3.13)$$

Sustainability Index

Loucks, (1997) proposed a sustainability index which combines the three measures – reliability, resilience and vulnerability ratio. It is expressed as:

$$\text{Re}\,l_t * \text{Re}\,s \left(1 - \frac{Vul_{\max}}{D} \right) \qquad 0 \le \text{k} \le 1 \qquad (3.14)$$

Where, D = target demand.

4.0 RESULTS AND DISCUSSION

4.1 River-inflow

Australian Water Balance Model (AWBM) was run for a period of 30 years on daily basis and yielded the results in Figures 11 and 12 for both calibration and validation period. The quantitative model performance is shown in Table 5. The model was able to capture the flows during both calibration and validation period. According to Moriasi et al (2007), NSE ranges between $-\infty$ and 1.0 with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally considered as acceptable levels of performance, whereas values ≤ 0 which indicates that the mean observed value is a better predictor than the simulated value, is considered as unacceptable performance. Model calibration and verification were considered satisfactory in his study only when NSE ≥ 0.65 and r ≥ 0.80 were obtained for daily streamflow comparison.

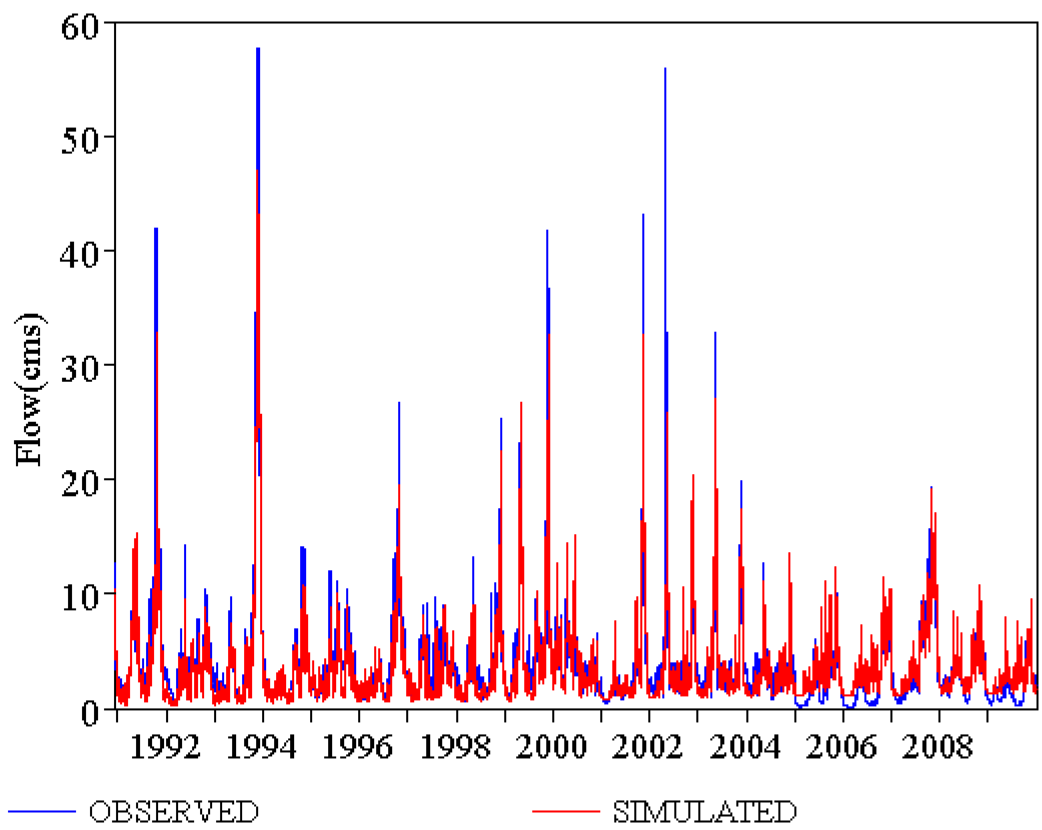


Figure 11. Daily observed and simulated runoff for calibration period.

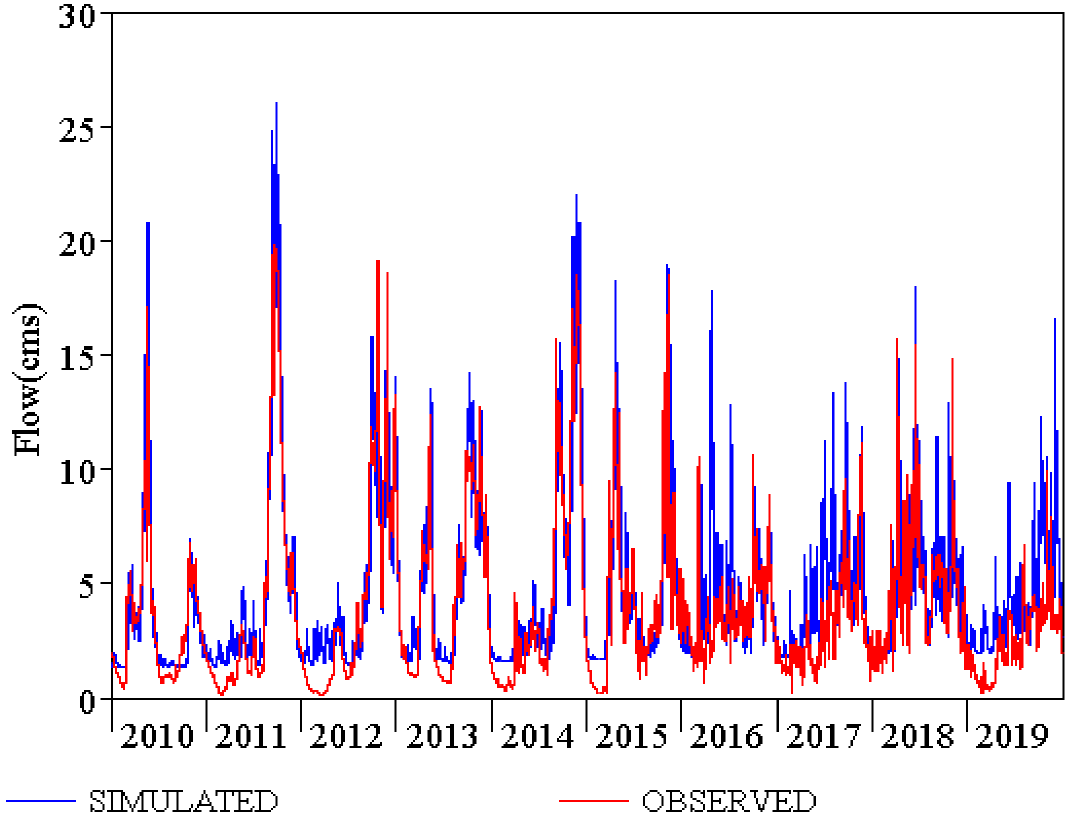


Figure 12. Daily observed and simulated runoff for validation period.

A good match between the observed and simulated flow values was realized as shown in the Figures 11 and 12 for both calibration and validation period but with some overestimates of flow in 2011 and 2015, and underestimates in 2018 during the validation period. This is because, the use of the NSE during calibration makes traditional models to perform better for high flows than low flows (Onyutha, et al 2020).

The Nash Sutcliff for validation and calibration ranged from good to very good according to Singh et al (2004). RMSE-observations standard deviations ratio (RSR) computed as the ratio of RMSE to standard deviation of the observed flow of the overall simulation was 0.46 which was very good as it was within the range of 0 and 0.5 as stated by Singh et al (2004). The RMSE values (Table 5) were large because high flows and low flows are of large and small magnitudes respectively. Therefore, the differences between observed and modelled flows were larger for high flows than low flows.

The NSE of calibration was higher than that for validation period in the study. This is due to the difficulty in transfering the model performance with respect to the variation in the catchment hydro-climatic conditions over time (Onyutha, et al 2020).

Onyutha, (2016) applied AWBM in the simulation of moderate and extreme flows on Blue Nile basin and was the best in performance compared to other models (Tank, SAC, SIMHYD, SMAR) as it produced the highest Nash Sutcliff efficiency of 0.86. Onyutha, et al (2020) also applied AWBM on River Kafu catchment in Uganda with similar characteristics to the study area and the model yielded appealing results with an overall Nash Sutcliff efficiency of 0.7 and the R-squared of above 50% compared to other hydrological models.

The results in Figures 11, 12 and Table 5 yielded by Australian Water Balance Model and consistency in performing well in different studies shows that it is good at simulating river inflow in Wambabya River catchment.

Table 5. Model performance indices.

Period	NSE	R^2	RMSE (m^3/s)	RSR
Calibration	0.758	0.74	2.26	0.53
validation	0.67	0.74	2.05	0.62

4.2 Optimal reservoir operation

HEC-ResSim model was run from 2012 - 2019 which includes a look back, calibration and validation period. This is the period for which the historic dam and reservoir data was available. Since reservoir sedimentation was not considered in the study, reservoir capacity curves were not adjusted. The model performed better with Nash and Sutcliffe coefficient, root mean square error and coefficient of determination for calibration and validation as shown in Table 6. The R^2 coefficient measures the degree of collinearity between the simulated and observed levels and Nash Sutcliffe coefficient is a measure of the predictive power of a hydrological model. The model yielded a Nash Sutcliffe and RMSE-observations standard deviations ratio (RSR) which is very good according to the guideline suggested by Singh et al (2004).

Table 6. HEC-ResSim model performance indices

Period	NSE	R^2	RMSE (m^3/s)	RSR
Calibration	0.85	0.84	1.49	0.36
Validation	0.82	0.85	0.54	0.26

The HEC-ResSim model performance was also evidenced with the graphical illustrations in Figures 13 and 14 which showed a good match on the simulated releases with the observed downstream flows for the simulation period. Just still like any other model, The NSE for calibration was higher than that for validation period in the study. This could be due to the difficulty in transfering the model performance from one model simulation period to the other (Onyutha, et al 2020).

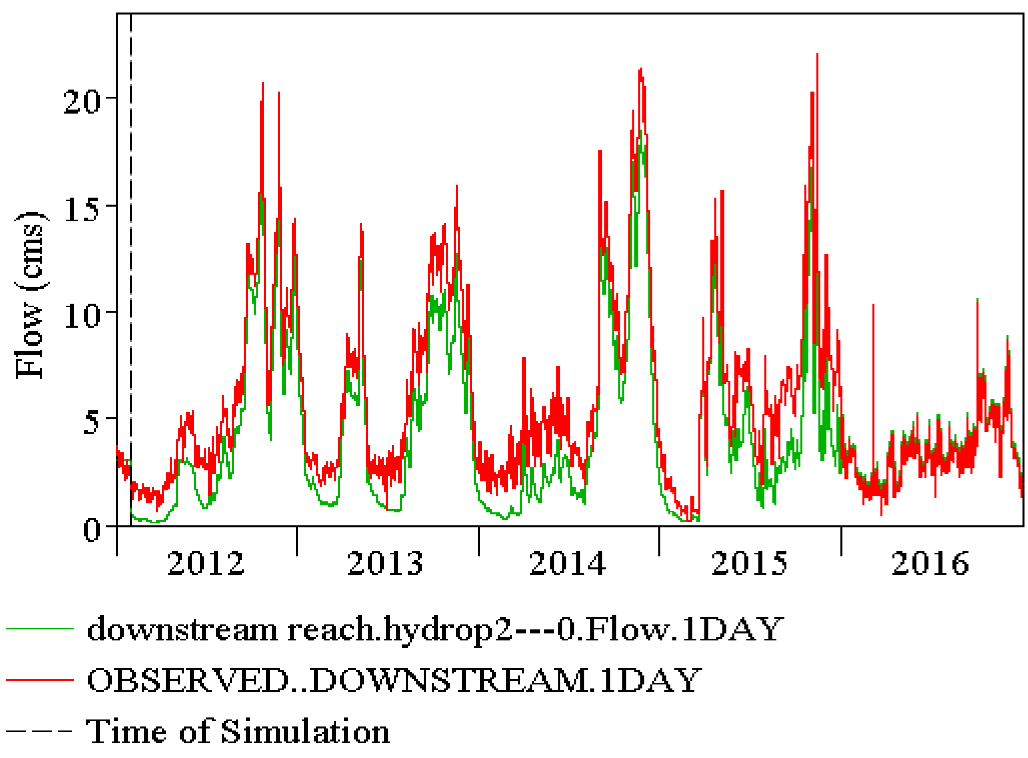


Figure 13. HEC-ResSim model calibration results.

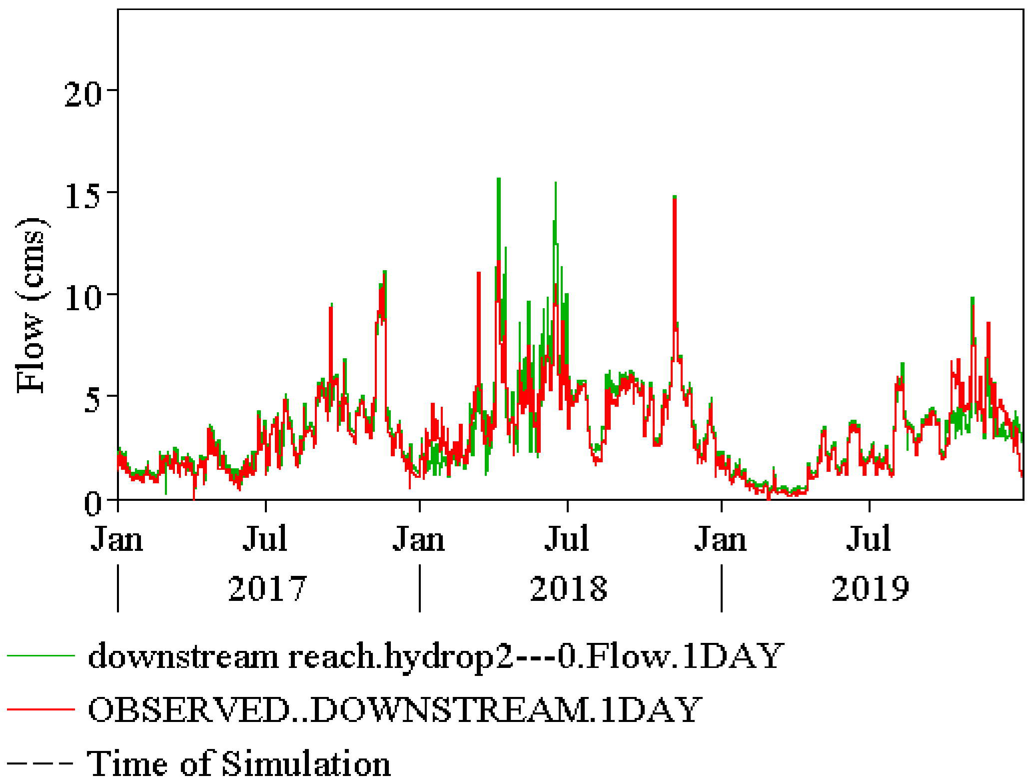


Figure 14. HEC-ResSim model verification results.

Table 7. Reservoir summary report

Parameter/location	Average	Maximum	Minimum
Storage (m^3)	58,142.31	84,308.00	23,392.67
Elevation (m)	957.67	959.00	955.94
Uncontrolled spills (m^3/s)	0.89	2.20	0.00

The results in Table 7 shows that the reservoir will be able to maintain a minimum storage of 23,392.67 m^3 which is higher than the observed storage of 12,300 m^3. Additionally, the spills have been minimized to 2.2 m^3/s less than the observed recorded spills over the spillway. This implies that much water will be stored in the reservoir at flood pool raising the head for power generation and preserving water for use during periods of low inflows into the reservoir.

Table 8. Reservoir storage volumes (m^3)

	2013	2014	2015	2016	2017	2018	2019
JAN	60009.4	18804.6	21710.3	36108.2	34216.8	34216.8	33914.5
FEB	24080.7	1917.2	616.6	24087.0	24062.2	24087.0	3035.9
MAR	22534.3	7231.4	29097.9	34078.4	34093.4	42493.1	3839.8
APR	89370.8	55349.6	58961.6	55349.6	51337.4	81637.7	29905.3
MAY	83244.1	65011.0	65011.0	65011.0	60119.6	67234.9	65011.0
JUN	45856.1	65011.0	68088.9	65011.0	64792.2	77199.5	65011.0
JUL	8728.9	65011.0	62664.7	65011.0	65011.0	65011.0	65011.0
AUG	65011.0	65011.0	65011.0	65011.0	65011.0	65011.0	65045.9
SEP	74981.1	74981.1	74981.1	74981.1	74981.1	74981.1	74981.1
OCT	84308.0	89991.3	84308.0	84308.0	84308.0	84308.0	84308.0
NOV	94246.9	100200.0	82890.2	74337.9	84855.1	78352.5	76100.7
DEC	67037.3	79685.5	63886.0	58224.3	54079.2	54694.1	55016.5

The Table 8 shows the reservoir pool storage levels for the simulation period which if maintained in the reservoir with the corresponding reservoir elevations in Table 9 with varying reservoir inflows from Wambabya River, an appreciable reliability of 91% of the reservoir system will be realized which will yield better hydropower benefits. This is because effectiveness of hydropower generation is based on reservoir operating rule curves involving relations among hydropower plant's efficiency, flow rate, reservoir water head and storage.

Through the entire simulation of the HEC-ResSim model, the control rule curve of Kabalega reservoir was derived. A comparison of this curve with the original rule curve of the reservoir, showed a difference in the operation and elevations as tabulated in Table 9.

Table 9. Current and new conservation rule curve

Month	New	Current
January	957.0	956.0
February	956.0	956.0
March	956.0	956.0
April	957.0	957.0
May	958.0	957.0
June	958.0	956.0
July	958.0	956.0
August	958.0	958.0
September	958.0	958.0
October	959.0	958.0
November	959.0	958.0
December	958.0	956.0

Table 10. Power summary report

Parameter	Average	Maximum	Minimum
Generation Efficiency	0.88	0.89	0.87
Power Head (m)	319.04	321.35	316.32
Hydraulic Losses (m)	0.5	0.5	0.5
Energy Generated per time step (MW)	174.44	248.4	4.74
Power Generated (MW)	7.27	10.35	0.22
Flow Power (m^3/s)	2.62	3.76	0.07

The results of simulated average power generated under the new operation policy shows an increase in power compared to the observed average power of 5.3 MW generated under the original design operation rule. This is could be associated to the new rule being able to allow water storage maintaining a higher target elevation which allows the reservoir maintain head for hydropower production. A minimum flow release of 2.62 m^3/s should also be maintained to ensure a power generation of 7.27 MW which meets demand for 91% of the time.

The release decision logic in HEC-ResSim starts and ends with the guide curve. The top of conservation zone here was used as a guide curve. When the reservoir's pool elevation was above the guide curve (in flood zone), the reservoir released more water than was entering the pool. when below the guide curve (in conservation), the reservoir released less water than was entering the pool. All operating rules and physical limitations acted as constraints upon the reservoir's ability to meet the goal of returning the pool to its guide curve elevation.

A maximum type rule was assigned to the flood pool to limit the release that could be made to evacuate the flood pool. When reservoir inflows exceed this limit, the reservoir will store water in the flood pool. The rule was also assigned to the conservation pool so that the release limit can be enforced as the reservoir level transitions from conservation to flood pool. Raising reservoir elevation to flood pool allows to cut back releases so as to store water to use during drought period.

A minimum required flow rule (which requires releases be larger than minimum amount) was assigned to the flood pool, this can not constrain guide-curve operation as it empties the flood pool. Therefore, the reservoir was still able to release as much water as possible (up to the outlet capacity) to evacuate the flood pool and maintain the guide curve level.

4.3 Reservoir system performance

The simulation model was run for a period of 8 years, on a daily time step from 1st January 2012 to 31st December 2019 for which the historical data were available. The performance of reservoir system was assessed as per the discussed methodology by computing the values of various performance indices as tabulated in Table 11. The performance criteria for the reservoir system was analyzed from 1st January 2016 - 31st December 2019 due to the availability of historic power demand data for this period.

Table 11. Reservoir system performance criteria

Performance criteria		Value
Reliability		0.906
Time based reliability Rel_t		0.906
Occurrence based reliability	2016	0.926
	2017	0.863
	2018	0.915
	2019	0.921
Resilience		0.80
Vulnerability		0.80
Sustainability index		0.70

On analysing the results of the simulation model, it is revealed that the system exhibits a high reliability, thereby ensuring sufficient water supply for power generation and maintaining the ecological environment. This high reliability values implies lower risk value for the reservoir performance system in terms of balancing power production and demand.

Since resilience measures the system recovery from unsatisfactory state to a satisfactory state, the resilience index equal to 0.8 indicates that the system will recover from failure as a few failure events were observed. Vulnerability is associated with the severity of failure or damages. With this value of 0.8, the severity of failure of the reservoir system operation to meet the power demand is low.

Sustainability index (SI) value of 0.7 correspond to low or no stress of water supply (demand ≤ 80% of the potential water supply). This implies that the new operation policy will ensure a sustainable water supply for both hydropower generation and ecological use.

The increased reliability, resilience and low vulnerability implies a better system performance which could be attributed to new operation policy being able to allow water storage for use during periods of low inflows to the reservoir.

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The simulation of River Wambabya inflow using Australian Water Balance Model (AWBM) yielded appealing results as illustrated by the timeseries plots of simulated and observed flows and the quantitative statistical performance measures. The use of the model in other catchments therefore requires calibration and testing to site-specific catchments characteristics.

The HEC-ResSim simulation model results indicate that the modified/ derived operation policy is a surplus system with high reliability of achieving the targets and with short duration failures of insignificant amounts and a good recovery from unsatisfactory state to a satisfactory state. It thus implies that these rule curves are effective tools in guiding decision makers in the release of water without emptying the reservoirs but at the same time satisfying the demands based on the inflow, initial storage and end of month storage. It was revealed that the modified control rule curve of the reservoir didn't match with the original rule curve. The modified control rule elevations were higher than the original rule curve elevations in the months of January, May - July and October-December. This rule curve allowed storage of water at the normal flood zone especially during periods of high inflows in the months of October - December months. The stored water could be used during months of January - March and June and July which are characterized with low inflows into the reservoir.

The operation policies derived from the HEC-ResSim model simulation for each month are more stable and adaptable for release decisions due to fluctuations in the inflows into the reservoir and thus recommend them for use in the operation of Kabalega reservoir to maximize the benefits.

5.2 Recommendations

This study recommends the following to be included in future studies to be carried out in the catchment for better management of the basin water.

This study has not considered seepage from Kabalega reservoir as though its quantification and simulation of seepage from the reservoir can alter result obtained from HEC-ResSim and mode of operation of a reservoir. Therefore, the study recommends including this parameter in future studies. Penman –Monteith method of determining evapotranspiration also was not used due to inadequate data within the catchment.

Reservoir sedimentation is mostly one of the factors which deteriorates and throws a dam out of service. In fact, it is the determining factor while deciding the life span of reservoirs. The study therefore recommends watershed management practices that can curb the sediment yield into the reservoir.

Mathematical analysis of inflow forecasting for optimal operational policy development, along with simulation of reservoir system for optimal power generation should also be considered in further studies as climate change is an influential factor which normally affects reservoir operation.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (2006). *Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper*. *No. 56*, 173.

Amirhamzeh, H. (2012). Derivation of a single reservoir operation rule curve using genetic algorithm. *Recent Advances in Engineering*, 295–299.

Ankit, B., & Tiwari, D. H. L. (2015). Rainfall Runoff Estimation using RRL Toolkit. *International Journal of Engineering Research And*, *4*(05), 595–599. https://doi.org/10.17577/ijertv4is050761

Anorld, J. . . M., Gassman, D. . ., Abbaspour, P. . ., White, K. . ., Srinivasan, M. . ., Santhi, R., Harmel, C., Griensven, R. . . Van, Liew, A. Van, Kannan, M. ., & N Jha, M. . . (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1491–1508.

Asefa, D. (2011). *Water Use and Operation Analysis of Water Resource Systems in Omo Gibe River Basin* (Issue May). Addis Ababa University.

Bashar, K. E., Mutua, F., Mulungu, D. M. M., Deksyos, T., & A., S. (2005). Appraisal study to select suitable Rainfall-Runoff model (s) for the Nile River Basin. *Proceedings of International Conference of UNESCO Flanders Fust Friend/Nile Project.*, *1215*, 1–14.

Bergström, S. (1992). The HBV model - its structure and applications. In *SMHI reports Hydrology* (Issue 4).

Berhe, F. T., Melesse, A. M., Hailu, D., & Sileshi, Y. (2013). MODSIM-based water allocation modeling of Awash River Basin, Ethiopia. *Catena*, *109*, 118–128. https://doi.org/10.1016/j.catena.2013.04.007

Beven, K. (2012). Rainfall-Runoff Modelling. In *Rainfall-Runoff Modelling*. https://doi.org/10.1002/9781119951001

Beven, K. J., & Kirkby, M. J. (1979). A physically based , variable contributing area model of basin hydrology. *Hydrological Sciences-Bulletin*, *24*(1), 43–69. https://doi.org/10.1080/02626667909491834

Beven, K. J., Kirkby, M. J., Schofield, N., & Tagg, A. F. (1984). Testing a physically-based flood forecasting model (TOPMODEL) for three U.K catchments. *Journal of Hydrology*, *69*, 119–143.

Biondi, D., Freni, G., Iacobellis, V., Mascaro, G., & Montanari, A. (2012). Validation of hydrological models: Conceptual basis, methodological approaches and a proposal for a code of practice. *Physics and Chemistry of the Earth*, *42–44*, 70–76. https://doi.org/10.1016/j.pce.2011.07.037

Boughton, W. (2004). The Australian water balance model. *Environmental Modelling and Software*, *19*(10), 943–956. https://doi.org/10.1016/j.envsoft.2003.10.007

Bravo, J. M., Collischonn, W., Pilar, J. V., & Tucci, C. E. M. (2006). Reservoir operation rules optimization using an evolutionary algorithm. SouthEast water resource symposium. *SouthEast Water Resource Symposium*.

Burn, D. H., Venema, H. D., & Simonovic, S. P. (1991). Risk-based performance criteria for real-time reservoir operation. *Canadian Journal of Civil Engineering*, *18*(1), 36–42. https://doi.org/10.1139/l91-005

CEIWR-HEC. (2009). *HEC-DSSVue HEC Data Storage System Visual Utility Engine User's Manual*.

Chang, F. J., Chen, L., & Chang, L. C. (2005). Optimizing the reservoir operating rule curves by genetic algorithms. *Hydrological Processes*, *19*(11), 2277–2289. https://doi.org/10.1002/hyp.5674

Chen, T., Ren, L., Yuan, F., Yang, X., Jiang, S., Tang, T., Liu, Y., Zhao, C., & Zhang, L. (2017). Comparison of spatial interpolation schemes for rainfall data and application in hydrological modeling. *Water*, *9*, 1–18. https://doi.org/10.3390/w9050342

Das, S. (2019). Extreme rainfall estimation at ungauged sites: Comparison between region-of-influence approach of regional analysis and spatial interpolation technique. *International Journal of Climatology*, *39*(1), 407–423. https://doi.org/10.1002/joc.5819

David Ford, Pingel, N., & DeVries, J. J. (2008). *Hydrologic Modeling System - HEC-HMS - Applications Guide*. US Army Corps of Engineers Hydrologic Engineering Center, HEC.

Dawson, C. W., & Wilby, R. L. (2001). Hydrological modelling using artificial neural networks. *Progress in Physical Geography*, *25*(1), 80–108. https://doi.org/10.1177/030913330102500104

Debnath, D., Stoecker, A., Boyer, T., & Sanders, L. (2009). Optimal Allocation of Reservoir Water. *Southern Agricultural Economics Association Annual Meeting*, 24.

DHI. (2003). *MIKE BASIN. A Versatile Decision Support Tool For Integrated Water Resources Management Planning* (p. 38). DHI Water & Environment. www.dhisoftware.com, www.dhi.dk

Donigian, A. ., Bicknell, B. ., & Imhoff, J. . (1995). Hydrological Simulation Program-FORTRAN (HSPF). In V. . Singh (Ed.), *Computer models of watershed hydrology* (pp. 395–442).

Duan, Q. ., Gupta, V. ., & Sorooshian, S. (1993). Shuffled Complex Evolution Approach for Effective and Efficient Global Minimization. *Journal of Optimization Theory and Applications*, *3*(3), 501–521.

Fagot, Bartel, A. and S. (2011). Development of a restricted reservoir operating plan at west. *31st Annual USSD Conference San Diego. California*.

Goodarzi, E., Ziaei, M., & Shokri, N. (2013). Reservoir operation management by optimization and stochastic simulation. *Journal of Water Supply: Research and Technology - AQUA*, *62*(3), 138–154. https://doi.org/10.2166/aqua.2013.020

Goovaerts, P. (2000). Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. *Journal of Hydrology*, *228*(3), 113–129.

Guo, S. L., Zhang, H. G., & Chen, H. (2004). A reservoir flood forecasting and control system in China. *Hydrological Science Journal*, *49*(6), 959–972.

Gupta, H. V, Beven, K. J., & Wagener, T. (2005). Model Calibration and Uncertainty Estimation. *Encyclopedia of Hydrological Sciences*, 1–17. https://doi.org/10.1002/0470848944.hsa138

Haque, M. M., Rahman, A., Hagare, D., & Kibria, G. (2015). Parameter uncertainty of the

AWBM model when applied to an ungauged catchment. *Hydrological Processes*, *29*(6), 1493–1504. https://doi.org/10.1002/hyp.10283

Hargreaves, G. H., & Allen, R. G. (2003). History and evaluation of Hargreaves Evapotranspiration equation. *Journal of Irrigation and Drainage Engineering*, *129*(1), 53–63. https://doi.org/10.1061/(ASCE)0733-9437(2003)129:1(53)

Hashimoto, T., Stedinger, J. R., & Loucks, D. P. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resources Research*, *18*(1), 14–20. https://doi.org/10.1029/WR018i001p00014

Ho Ming, K., & Fadhilah, Y. (2012). Series, Homogeneity Tests on Daily Rainfall Malaysia, in Peninsular. In *Int. J. Contemp. Math. Sciences* (Vol. 7, Issue 1, pp. 9–22).

Hydrologic Engineering Centre. (2007). *Routing Methods and Techniques: Training materials*.

Jain, S. ., & Singh, V. . (2003). *Water resources systems planning and management*. Elsevier Science B.V.

Jebbo, B. E. A., & Awchi, T. A. (2016). Simulation Model for Mosul Dam Reservoir Using HEC-ResSim 3 . 0 Package ZANCO Journal of Pure and Applied Sciences Simulation Model for Mosul Dam Reservoir Using HEC-ResSim 3 . 0 Package 2003 by US Army Corps of Engineers (USACE) instead of (HEC-5) pa. *Journal of Salahaddin University-Erbil*, *28920*(August), 92–98.

Kjeldsen, T. R., & Rosbjerg, D. (2001). A framework for assessing the sustainability of a water resources system. *IAHS-AISH Publication*, *268*, 107–113.

KKhan, N. M., & Tingsachali, T. (2008). Optimization and simulation of reservoir operation with sediment evacuation: a case study of the Tarbela Dam, Pakistan. *Hydrological Processes*, *2274*(14 November 2008), 730–747. https://doi.org/DOI: 10.1002/hyp.7173

Klipsch, J. D., & Hurst, M. B. (2007). *HEC-ResSim Reservoir System Simulation User 's Manual Version 3.0* (Issue CPD-82).

Klipsch, J. D., & Hurst, M. B. (2013). *HEC-ResSim Reservoir System Simulation User's Manual Version 3.1* (Issue CPD-82). www.hec.usace.army.mil

Knapp, H. V., Durgunoglu, A., & Ortel, T. W. (1991). A Review of Rainfall-Runoff Modeling for Stormwater Management. *Illinois State Water Survey, Hydrology Division, SWS Contract Report 516*, 96.

Kokkonen, T., Koivusalo, H., & Karvonen, T. (2001). A semi-distributed approach to rainfall-runoff modelling - A case study in a snow affected catchment. *Environmental Modelling and Software*, *16*(5), 481–493. https://doi.org/10.1016/S1364-8152(01)00028-7

Labadie, J. W. (2006). MODSIM: Decision support system for integrated river basin management. *Proceedings of the IEMSs 3rd Biennial Meeting," Summit on Environmental Modelling and Software"*.

Lam, K. C., Bryant, R. G., & Wainright, J. (2015). Application of spatial interpolation method for estimating the spatial variability of rainfall in Semiarid New Mexico, USA. *Mediterranean Journal of Social Sciences*, *6*(4 S3), 108–116. https://doi.org/10.5901/mjss.2015.v6n4s3p108

Lara, P. G., Lopes, J. D., Luz, G. M., & Bonumá, N. B. (2014). Reservoir operation employing HEC-ResSim: Case study of Tucuruí dam, Brazil. *6th International Conference on Flood Management, September 2014*, 1–12. https://doi.org/10.13287/j.1001-9332.20140123.0051

Lee, S. Y., Fitzgerald, C. J., Hamlet, A. F., & Burges, S. J. (2011). Daily Time-Step Refinement of Optimized Flood Control Rule Curves for a Global Warming Scenario. *Journal of Water Resources Planning and Management*, *137*(4), 309–317. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000125

Liang-Cheng, C., Chih-Chao, H., & Yu-Wen, C. (2010). Applying multiobjective genetic algorithm to analyze the conflict among different water use sectors during drought period. *Journal of Water Resources Planning and Management*, *136*(5), 539–546. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000069

Lloyd, C. D. (2005). Assessing the effect of integrating elevation data into the estimation of monthly precipitation in Great Britain. *Journal of Hydrology*, *308*(1–4), 128–150. https://doi.org/10.1016/j.jhydrol.2004.10.026

Loucks, D. P. (1997). Quantifying trends in system sustainability. In *Hydrological Sciences-*

Journal-des Sciences Hydrologiques (Vol. 42, Issue 4). https://doi.org/10.1080/02626669709492051

Loucks, D. P., & Beek, E. van. (2007). Water resource systems planning and analysis. In *springer* (Vol. 4, Issue 3). Deltares and UNESCO-IHE. https://doi.org/10.1007/978-3-319-44234-1

Lu, G. Y., & Wong, D. W. (2008). An adaptive inverse-distance weighting spatial interpolation technique. *Computers and Geosciences*, *34*, 1044–1055. https://doi.org/10.1016/j.cageo.2007.07.010

Mamman, M. J. (2018). Recalibration of kainji reservoir operating rule for optimal operation. *Annals of Reviews and Research*, *1*(1), 0023–0029.

Mariam, M. G. (2012). *Modeling of Tekeze Hydropower Reservoir Operation with HEC–ResSim*. Addis A baba University.

Masindi District Environment Department. (2005). *District State of Environment Report 2004*.

Moriasi, D. N., Arnold, J. G., Liew, M. W. Van, Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines For Systematic Quantification of Accuracy in Watershed Simulations. *American Society of Agricultural and Biological Engineers*, *50*(3), 885−900. https://doi.org/10.1234/590

Mubialiwo, A., Onyutha, C., & Abebe, A. (2020). Historical Rainfall and Evapotranspiration Changes over Mpologoma Catchment in Uganda. *Advances in Meteorology*, *2020*(March 2010). https://doi.org/10.1155/2020/8870935

Mujumdar, P. P., & Nirmala, B. (2007). A Bayesian stochastic optimization model for a multi-reservoir hydropower system. *Water Resources Management*, *21*(9), 1465–1485. https://doi.org/10.1007/s11269-006-9094-3

Nash, J. E., & Sutcliffe, J. V. (1970). River Flow Forcasting Through Conceptual Models. *Journal of Hydrology*, *9*(2), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6

OLani, W. T. (2006). *Operational Analysis of the Cascadded Wadecha-Belbela Reservoir System (ADA ' A liben Woreda , in Oromia Region)*. Arbaminch University.

Onyutha, C, Amollo, C, J., Nyende, J., & Nakagiri, A. (2020). Suitability of averaged outputs from multiple rainfall - runoff models for hydrological extremes : a case of River Kafu catchment in East Africa. *International Journal of Energy and Water Resources, 0123456789*, 1–14. https://doi.org/10.1007/s42108-020-00075-4

Onyutha, Charles. (2016). Influence of Hydrological Model Selection on Simulation of Moderate and Extreme Flow Events: A Case Study of the Blue Nile Basin. *Advances in Meteorology*, *2016*, 28. https://doi.org/10.1155/2016/7148326

Onyutha, Charles. (2017). *Variability of Rainfall and River Flow in the Nile Basin Variability of Rainfall and River Flow in the Nile Basin* (Issue September). Ku Leuven.

Pechlivanidis, I. G., Jackson, B. M., Mcintyre, N. R., & Wheater, H. S. (2011). Catchment scale hydrological modelling: A review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and applications. *Global Nest Journal*, *13*(3), 193–214. https://doi.org/10.30955/gnj.000778

Pellicone, G., Caloiero, T., Modica, G., & Guagliardi, I. (2018). Application of several spatial interpolation techniques to monthly rainfall data in the Calabria region (southern Italy). *International Journal of Climatology*, *38*(9), 3651–3666. https://doi.org/10.1002/joc.5525

Plumptre, A. J., Behangana, M., Davenport, T. R. B., Kahindo, C., Kityo, R., Ndomba, E., Nkuutu, D., Owiunji, I., Ssegawa, P., & Eilu, G. (2003). The Biodiversity of the Albertine Rift. Albertine Rift Technical Reports No. 3. *Biological Conservation*, *December 2015*, 178–194. https://doi.org/10.1016/j.biocon.2006.08.021

Ranch, H., & Simonovic, S. (1995). 123 Computer Models of Watershed Hydrology edited by Vijay P. Singh. *Director*.

Rani, D., & Moreira, M. M. (2010). Simulation-optimization modeling: A survey and potential application in reservoir systems operation. *Water Resour Manage*, *24*(6), 1107–1138. https://doi.org/10.1007/s11269-009-9488-0

Reddy, M. J., & Kumar, D. N. (2006). Optimal reservoir operation using multi-objective evolutionary algorithm. *Water Resources Management*, *20*(6), 861–878. https://doi.org/10.1007/s11269-005-9011-1

Refsgaard, J. ., & Storm, B. (1995). MIKE SHE. In V. P. Singh (Ed.), *Computer Models of Watershed Hydrology* (pp. 809–846). Water Resources Publications, Highlands Ranch.

Revelle, C. (1999). *Optimizing reservoir resources, including a new model for reservoir reliability.* (John Wiley and Sons (ed.)).

Rinsema, J. G., Franks, S., & Mekonnen, M. M. (2014). Comparison of Rainfall- Runoff Models for Floods Forecastings. *University of the Tasmania*, 54.

Rugumayo, A. I. (2012). *An Introduction to Hydrology and Water Resources Engineering in Uganda* (Issue June).

Sharma, P. J., Patel, P. L., & Jothiprakash, V. (2016). Efficient discretization of state variables in stochastic dynamic programming model of Ukai reservoir, India. *ISH Journal of Hydraulic Engineering*, *22*(3), 293–304. https://doi.org/10.1080/09715010.2016.1204632

SHEPARD D. (1968). Two- dimensional interpolation function for irregularly- spaced data. *Proceedings of the 23rd National Conference*, 517–524. https://doi.org/10.1145/800186.810616

Shiau, J. T., & Lee, H. C. (2005). Derivation of optimal hedging rules for a water-supply reservoir through compromise programming. *Water Resources Management*, *19*(2), 111–132. https://doi.org/10.1007/s11269-005-1502-6

Singh, J., Knapp, H. V., & Demissie, M. (2004). *Hydrologic Modeling of the Iroquois River Watershed Using HSPF and SWAT*.

Sorooshian, S., Gupta, H. ., Jasper, A. V., & Yilmaz, K. K. (1995). Model calibration in watershed hydrology. In *Water Resources Publications*. https://doi.org/10.1142/9789814307987_0003

Sorooshian, S., & Hamid, M. (2008). Hydrological Modelling and the Water Cycle: Coupling the Atmospheric and Hydrological Models. In *Water Science and Technology Library* (p. 294). Springer Science+ Business Media B.V. www.springer.com/series/6689

Suhaila, J., Deni, S. M., & Jemain, A. A. (2008). Detecting inhomogeneity of rainfall series in Peninsular Malaysia. *Asia-Pacific Journal of Atmospheric Sciences*, *44*(4), 369–380.

Taghian, M., Rosbjerg, D., Haghighi, A., & Madsen, H. (2014). Optimization of conventional rule curves coupled with hedging rules for reservoir operation. *Journal of Water Resources Planning and Management*, *140*(5), 693–698. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000355

Thiessen, A. . (1911). *Precipitation for large areas, Monthly Weather Review* (pp. 1084–1082).

U.S. Army Corps of Engineers (USACE). (1997). *Hydrologic Engineering Requirements for Reservoirs. Manual No. 110-2-1420*.

Uhlenbrook, S., Roser, S., & Tilch, N. (2004). Hydrological process representation at the meso-scale: The potential of a distributed, conceptual catchment model. *Journal of Hydrology*, *291*(3–4), 278–296. https://doi.org/10.1016/j.jhydrol.2003.12.038

Uysal, G., Akkol, B., Topcu, M. I., Sensoy, A., & Schwanenberg, D. (2016). Comparison of Different Reservoir Models for Short Term Operation of Flood Management. *Procedia Engineering*, *154*, 1385–1392. https://doi.org/10.1016/j.proeng.2016.07.506

Vaze, J., Jordan, P., Beecham, R., Frost, A., & Summerell, G. (2011). *Calibration Info eWater* (Issue Interim Version 1.0).

Wijngaard, J. B., Klein Tank, A. M. G., & Können, G. P. (2003). Homogeneity of 20th century European daily temperature and precipitation series. *International Journal of Climatology*, *23*(6), 679–692. https://doi.org/10.1002/joc.906

Winpenny, J. (1994). *Managing Water As An Economic Resource* (p. 133).

Wurbs, R. A. (1991). *Optimization of Multiple-Purpose Reservoir System Operations: A Review of Modeling and Analysis Approaches*.

Wurbs, R. A. (1993). Reservoir-System Simulation And Optimization Models. *J. Water Resour. Plann. Manage*, *119*(4), 455–472. https://doi.org/org/10.1061/(ASCE)0733-9496(1993)119:4(455)

Wurbs, R. A. (2005). *Comparative evaluation of generalized river/reservoir system models* (Issue Technical Report No. 282). https://doi.org/DOI: 10.1016/j.jhydrol.2004.06.003

WWF. (2006). *Lake Albert Eastern Catchment Management Initiative, Uganda: Baseline Study* *on Water Quality Monitoring Programme*. *October*, 1–117. http://www.savimaxx.co.ug/rpts/base.pdf

Zagona, E. T., Fulp, R., Shane, T. M., & Goranflo, H. M. (2001). Riverware: A generalized tool for complex reservoir systems modeling. *Journal of the American Water Resources*, 913–929.

Zagona, E., Tim, M., Steve, S., & David, N. (2006). *Demonstration of riverware*.

Zhang, Q., Liu, J., Singh, V. P., Gu, X., & Chen, X. (2016). Evaluation of impacts of climate change and human activities on streamflow in the Poyang Lake basin, China. *Hydrological Processes*, *30*(14), 2562–2576. https://doi.org/10.1002/hyp.10814

Zhou, Y., & Guo, S. (2013). Incorporating ecological requirement into multipurpose reservoir operating rule curves for adaptation to climate change. *Journal of Hydrology*, *498*, 153–164. https://doi.org/10.1016/j.jhydrol.2013.06.028

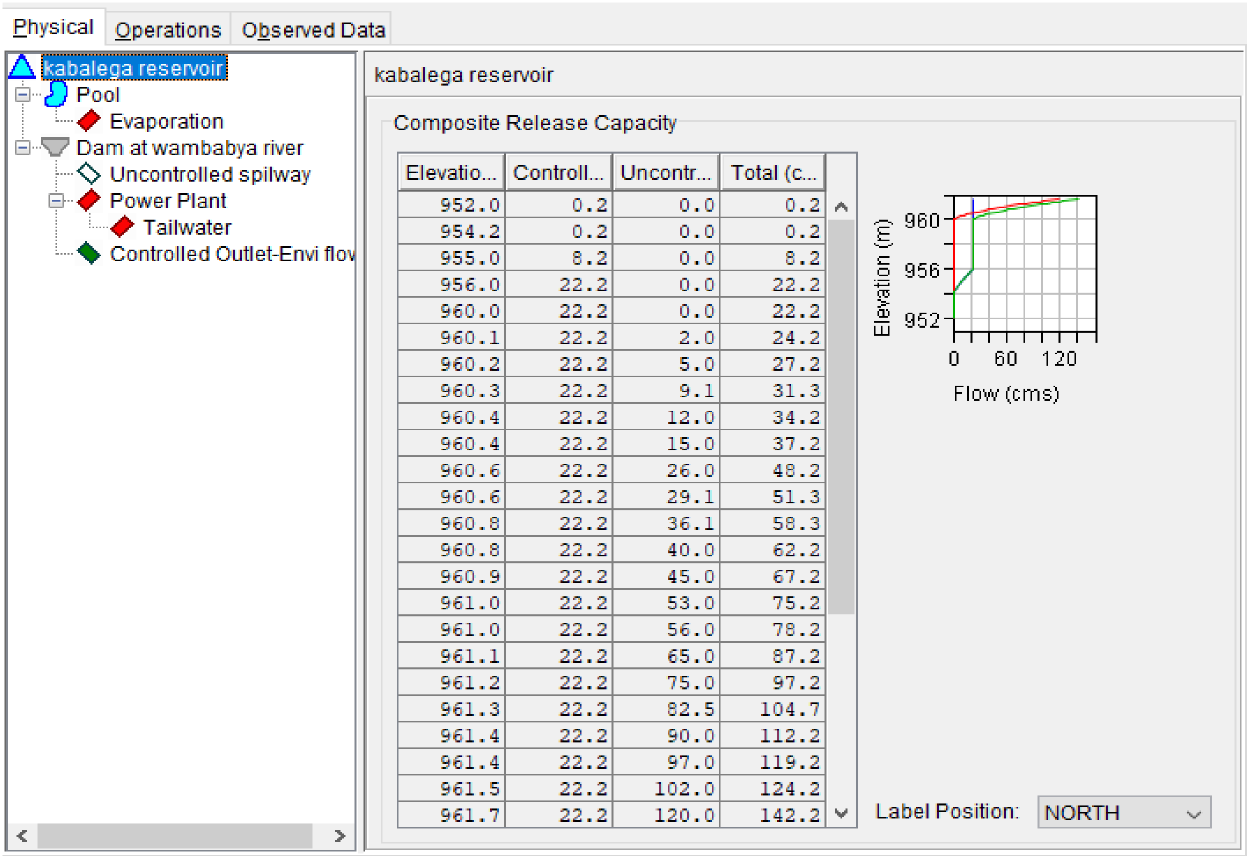
Ziaei, M., Shui, L. T., & Goodarzi, E. (2012). Optimization and simulation modelling for operation of the Zayandeh Rud Reservoir. *Water International*, *37*(3), 305–318. https://doi.org/10.1080/02508060.2012.688189

APPENDIX

Figure 15. River cross-section measurement (Photo 17th /02/2020).

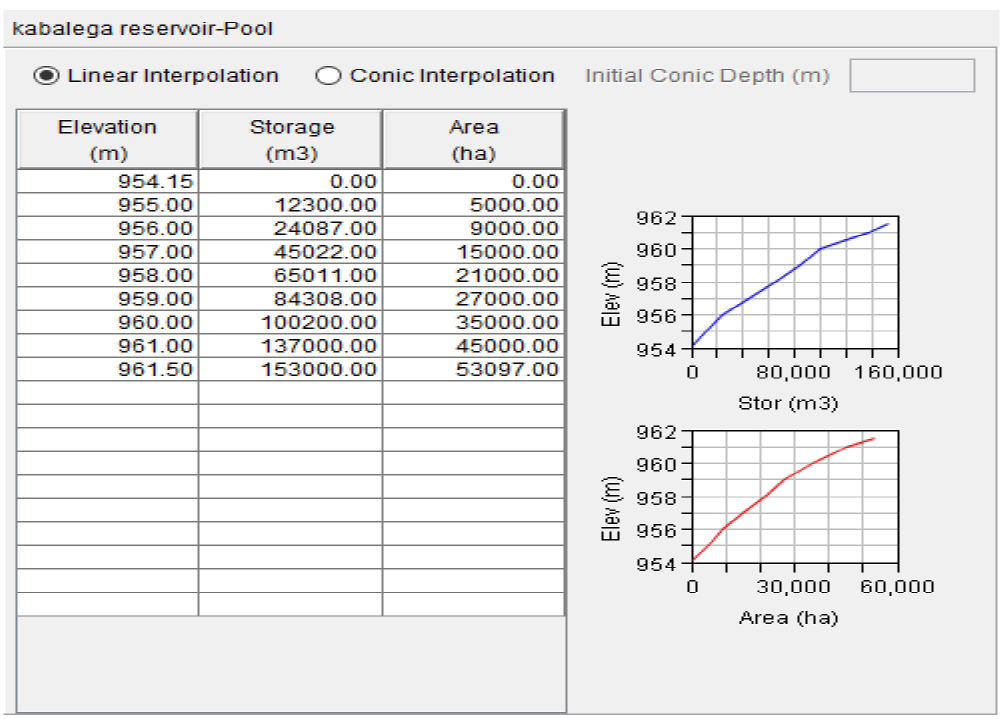
Figure 16. Kabalega reservoir (Photo 17th /02/2020).

Figure 17. Environment flow gate and unregulated spillway for Kabalega reservoir (Photo 17th /02/2020).



Elevatio...	Controll...	Uncontr...	Total (c...
952.0	0.2	0.0	0.2
954.2	0.2	0.0	0.2
955.0	8.2	0.0	8.2
956.0	22.2	0.0	22.2
960.0	22.2	0.0	22.2
960.1	22.2	2.0	24.2
960.2	22.2	5.0	27.2
960.3	22.2	9.1	31.3
960.4	22.2	12.0	34.2
960.4	22.2	15.0	37.2
960.6	22.2	26.0	48.2
960.6	22.2	29.1	51.3
960.8	22.2	36.1	58.3
960.8	22.2	40.0	62.2
960.9	22.2	45.0	67.2
961.0	22.2	53.0	75.2
961.0	22.2	56.0	78.2
961.1	22.2	65.0	87.2
961.2	22.2	75.0	97.2
961.3	22.2	82.5	104.7
961.4	22.2	90.0	112.2
961.4	22.2	97.0	119.2
961.5	22.2	102.0	124.2
961.7	22.2	120.0	142.2

Figure 18. Kabalega reservoir's physical components.



Elevation (m)	Storage (m3)	Area (ha)
954.15	0.00	0.00
955.00	12300.00	5000.00
956.00	24087.00	9000.00
957.00	45022.00	15000.00
958.00	65011.00	21000.00
959.00	84308.00	27000.00
960.00	100200.00	35000.00
961.00	137000.00	45000.00
961.50	153000.00	53097.00

Figure 19. Elevation- storage-area capacity curves

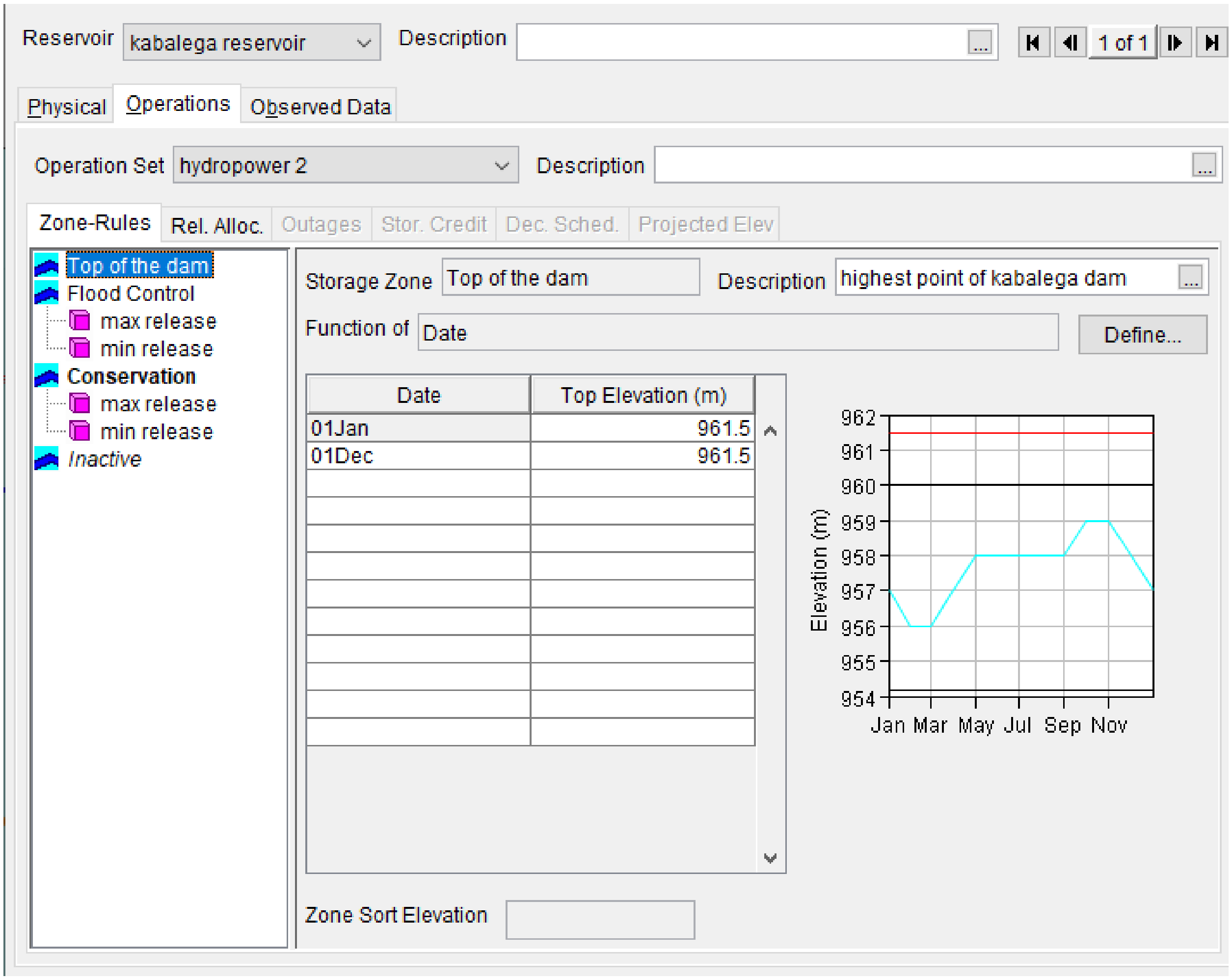


Figure 20. Kabalega Reservoir operations set.

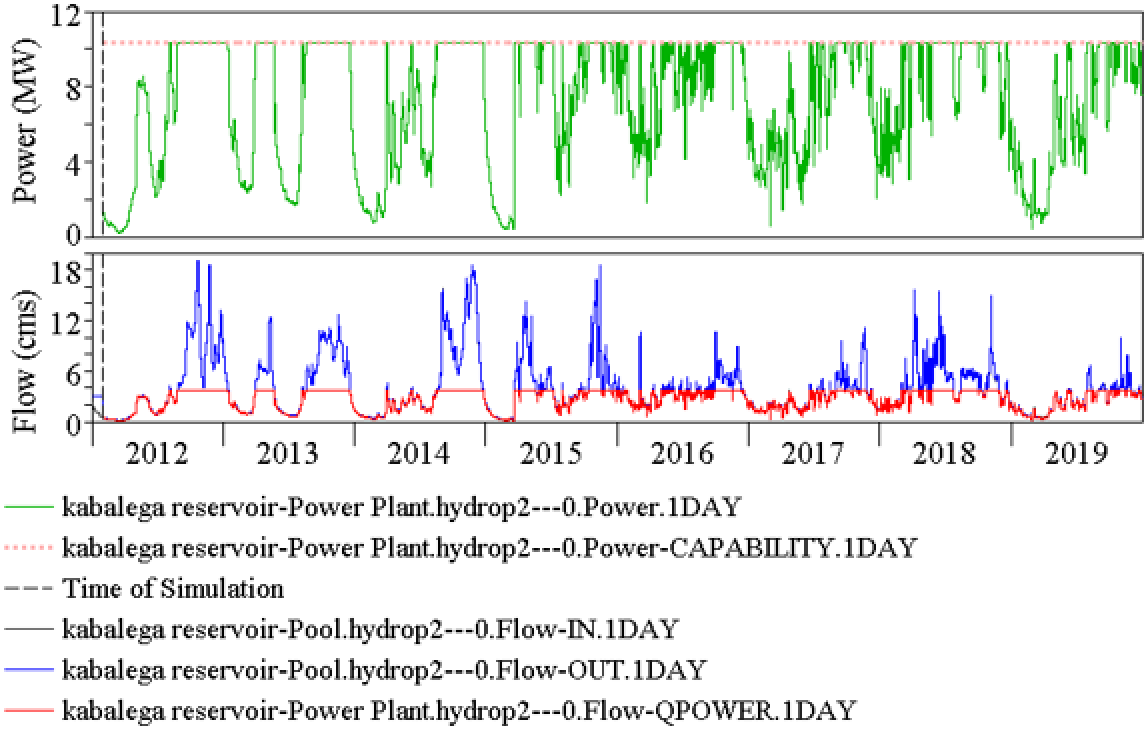


Figure 21. Kabalega reservoir simulated power

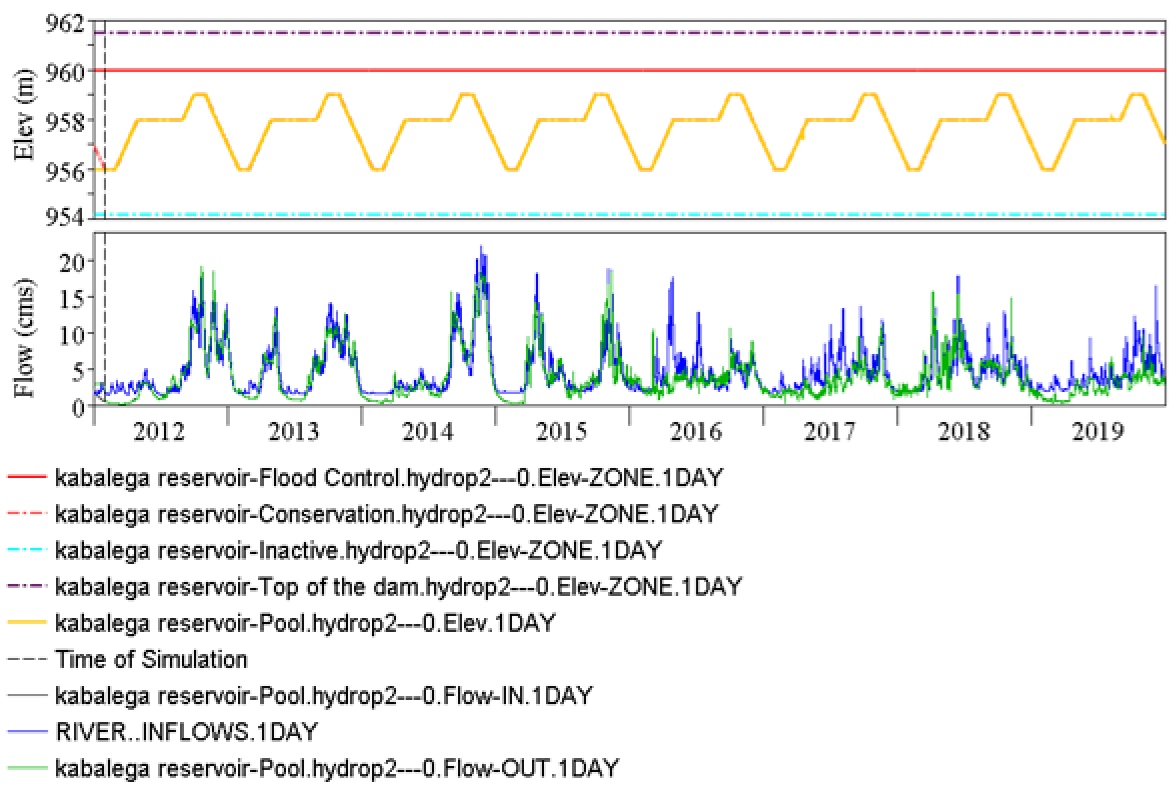


Figure 22. Kabalega reservoir operation zones with inflows and outflows

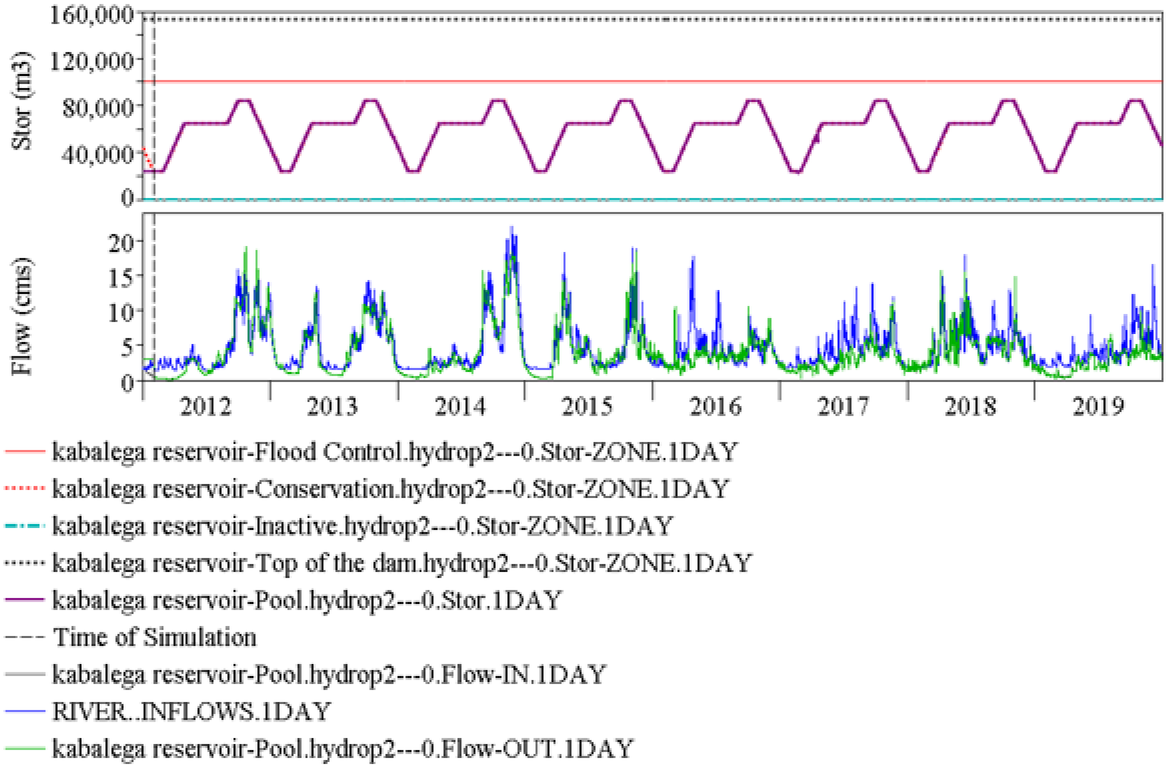


Figure 23. Kabalega reservoir operations