UNIVERSITY of RWANDA

APPLICATION OF WEAP MODEL FOR ASSESSMENT OF CURRENT & FUTURE WATER RESOURCES AVAILABILITY AND DEMANDS OF MUKUNGWA CATCHMENT, RWANDA

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Supervisor: Prof. Umaru Garba WALI

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DECLARATION

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature…………………………………….

Date………………………………………….

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Prof. Umaru Garba WALI,

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ABSTRACT

Water managers and policy makers require tools in order to achieve a balance in water supply and demand, to ensure equitable allocation of water resources, protect the environment, promote efficient use of water and develop priorities in shared water resources. The Water Evaluation and Planning System (WEAP) Model is one of such tools used for many river basins when dealing with the stochastic nature of stream flow and water use variables.

The overall objective of this thesis is to contribute to sustainable water resources management in Rwanda through assessment of current and future water resources availability & demands and developing water allocation plan for Mukungwa catchment using WEAP model as a Decision Support System (DSS).

The WEAP hydrologic modelling of Soil Moisture Method (SMM) was used to allow the most comprehensive analysis of characterization for land use and soil type. For allowing simulation of water balance and water allocation, the elements that comprise the water demand-supply system and their spatial relationships were characterized for the Mukungwa catchment.

The data used in this study were obtained through site visits and from different sources, including Government Agencies, private companies, NGO's and different websites for published papers and books.

In order to address a broad range of "what if" questions, three projection scenarios (2030 and 2050) were developed and their possible impacts on the catchment water balance evaluated.

- Scenario 1 considers an increase in population growth rate (increased population generates increased water demand);
- Scenario 2 considers an increase in economic development (sectoral water demands such as increase in irrigated areas, in industry and manufacturing, in mining, etc.);
- Scenario 3 deals with the implementation of an environmental flow requirement (ecosystems and downstream water demand).

The economy of the Mukungwa catchment relies strongly on rain-fed agriculture, both for rural livelihoods and exports. Horticulture is common in the catchment as the fertile soils in the area lead to high production levels of e.g. vegetables and Irish potato. Mining, both commercial and artisanal, is common and 'sand mining' in riverbeds is also an important economic activity. Volcanoes National Park is the main source of foreign currency from tourism activities, commercial activities, and fisheries development in Burera and Ruhondo Lakes. There is a large number of Hydropower Plants, supplying electricity to the whole country. A very small percentage, urban dwellers only, have house water connections; the remainder only have access to an unprotected spring or a river as their only (unimproved) source of water supply.

The results show that the total water availability in the catchment is estimated at 883.4 MCM annually, unevenly distributed in months. This includes surface runoff from the catchment area, base flow, and return flows. The minimum river flow occurs in the month of August and peak flows occur in the month of April.

The results of water demand during baseline year of 2020 show that the total annual water demand is about 48 Mm^3, where domestic is the largest water use sector, which comprises of

66% of total water demands equivalent to 31.7 Mm^3, followed by irrigation with 22% of total water demands equivalent to 10.4 Mm^3. The projected water demands are mainly influenced by population growth and socio-economic development in the catchment including irrigation sector. In 2030 projection for all scenarios including EFR, the annual water demands is expected to be 346.3Mm^3, while in 2050, water demands are expected to be 366.8Mm^3. The trend of consumptive water demand from 2020 up to 2050 shows that it is expected to increase at almost double in 2050.

The WEAP Modelling results on water availability confirm the statement of the National Water Resources Master Plan, saying, "*Mukungwa catchment is water tower of Rwanda*". However, it is recommended that water allocation should be applied based on water resources availability, by carefully considering the location point of abstractions vis a vis the location of existing hydropower plant, to avoid potential conflict. The development of artificial water storages is recommended for balancing water availability and demand across seasons.

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LIST OF ABBREVIATIONS

DEM:	Digital Elevation Model
DHI:	Danish Hydraulic Institute
DSS:	Decision Support System
EFRs:	Environmental Flow Requirements
ER:	Environmental Reserve
ET:	Evapotranspiration
FAO:	Food and Agriculture Organization of the United Nations
FDC:	flow-duration curve
GDP:	Gross Domestic Product
GIS:	Geographic Information System,
Ha:	Hectare
HDX:	Humanitarian Data Exchange
HPP:	Hydropower Plant
IWRM:	Integrated Water Resources Management
LCPDC:	Rwanda Least Cost Power Development Plan
LULC:	Land Use and Land Cover
MCM:	Million Cubic Meter
MCP:	Marginal Cost Pricing
Meteo-Rwanda:	Rwanda Meteorology Agency
MINICOM:	Ministry of Trade and Industries
Mm^3:	Million cubic meter
MODSIM:	Modular Simulator
NGO:	Non Governmental Organisation
NISR:	National Institute of Statistics of Rwanda
NST:	National Strategy for Transformation
NWRMP:	National Water Resources Master plan
PEST:	Parameter Estimation Tool
Pref. Dir:	Preferred Flow Direction
REALM:	Resource Allocation Model
REG:	Rwanda Energy Group
RIBASIM:	River Basin Simulation Model
RMB:	Rwanda Mining, Petrolium and Gas Board
RRF:	Runoff Resistance Factor
RWB:	Rwanda Water Resources Board
SEI:	Stockholm Environment Institute
SMM:	Soil Moisture Method
SWC:	Soil Water Capacity
TCM:	Thousand Cubic Meter
WaPOR:	Water Productivity Portal
WASAC:	Water and Sanitation Corporation
WEAP:	Water Evaluation and Planning System

1. INTRODUCTION

1.1. Background and Context

Water is one of the most essential resources on Earth and fundamental for life to exist. It is also needed for agriculture and other economic sectors. This natural resource is affected by many factors such as climatic variability, population growth, and economic development and create scarcity. Thus, this leads to implementation of effective water resources management, which becomes particularly important towards determining how much water is available for human use and economic activities that water should be shared between users. Water resource management is a multifaceted issue that becomes more complex when considering multiple nations' interdependence upon a single shared trans-boundary river basin (Teasley R.L. and McKenney D.C., 2013). Water managers and policy makers require tools in order to achieve a balance in water supply and demand, to ensure equitable allocation of water resources, protect the environment, promote efficient use of water and develop priorities in shared water resources (Loon A.V. and Droogers P, 2006). The Water Evaluation and Planning System (WEAP) Model is one of such tools used for many river basins when dealing with the stochastic nature of stream flow and water use variables. This model was developed by the Stockholm Environment Institute's (SEI) centre in the United States in 1990. It is a generic, integrated water resources planning software tool that provides a comprehensive, flexible and user friendly framework for the development of water balances, scenario generation, planning and policy analyses (Sieber J. and Purkey D., 2015). The development of water balance through a WEAP model requires a certain set of climate and hydrological data, as well as data on water supply and water demand in order to map the existing water resources and their utilisation within the basin (Dimova G., Tzanov E., Ninov Pl., Ribarova I. and Kossida M., 2013). The WEAP model integrates water demands with water supply (Yates D., Sieber J., Purkey D. and Lee A.H. , 2005). This integration of watershed hydrology with the water planning process makes WEAP particularly suitable to evaluate the potential impacts of population growth, economic growth and climate change on the water balance. Understanding the water balance of a basin is essential to determine how much water is available in the basin for consumptive requirements over a specific period of time and how that water should be shared between users in the planning process.

In this thesis, the WEAP model was used to simulate water resources in the Mukungwa River catchment, in the North-Western region of Rwanda, and conduct water balance under increased service levels due to increased population growth, economic development & EFRs and propose suitable water allocation among users. The modelling process consists of two main components, namely, the supply and demand components. The supply component comprises of the hydrological analysis of the rivers and the demand component comprises a growth projection based on domestic, industrial, Environmental Flow Requirements (EFRs) and irrigation activities.

Different water users (i.e., rural, urban, mining, irrigated agriculture, industry, power generation) are present in the catchment. There are several natural reserves that demand special protection and environmental flows are needed to preserve the ecosystems. The development of the mining industry and the construction of new power generation plants, along with the population growth, the consideration of environmental flows to downstream users, and the revitalization of small scale irrigation schemes are going to increase the water demands in the Mukungwa catchment. On the top of this, the variable hydrology and the effect of climate change make it difficult to quantify the available water resources to satisfy these increasing demands. Being able to assess the ability of the catchment to satisfy its future water demands is crucial in order to plan for the future and make wise decisions. The Rwanda Water Resources Board (RWB) has identified the use of modelling tools along with the use of the scenario analysis approach as important tools in order to achieve an integrated management of the catchments (RWFA, 2018). These have been described as important tools to help develop Catchment Management Plan and in general to help in the decision making process.

Computer based Decision Support Systems (DSS) are very useful tools to perform this kind of study, because they allow the user to forecast and evaluate the impacts of different future trends and strategies before implementing them. Since it is not possible to predict exactly how the water demands and other factors are going to evolve in the future; it was considered appropriate to use a scenario analysis approach in this study. A set of realistic scenarios can be built in order to account for the uncertainty in the evolution of the water demands, population growth, the implementation of the Environmental Reserve Infrastructure development, etc. A Decision Support System can then be used in order to evaluate the impacts of these different scenarios and help water managers and water users in the decision making process.

The Mukungwa catchment faces lack of clear information on water resources in terms of availability, allocation limit, uses and different scenarios of allocation based on current and future demand and environmental flows. Water requirements for domestic, industry, mining, coffee washing stations and hydropower plants should be integrated in the catchment based plan by using a developed water allocation model like WEAP. The application of a water permit system at Rwanda Water Resources Board (RWB) for any significant intervention in the natural hydrological cycle with the help of a well-established water allocation plan will further the aspired sustainability. As the Mukungwa catchment is considered as the water tower of the country; there is a need of a detailed analysis of water resources availability and inform the seasonal release for downstream users including Kigali city and other Eastern province parts which face the water scarcity issues during dry season. This clearly indicates that there is a need to analyse the water balance of the river basin and to formulate water allocation plan for present and future demands. In order to implement the water allocation principles, a consolidation of information which shows the relationships between the water usage and water resources is necessary. Figure 1 below, shows the Mukungwa Catchment location map.

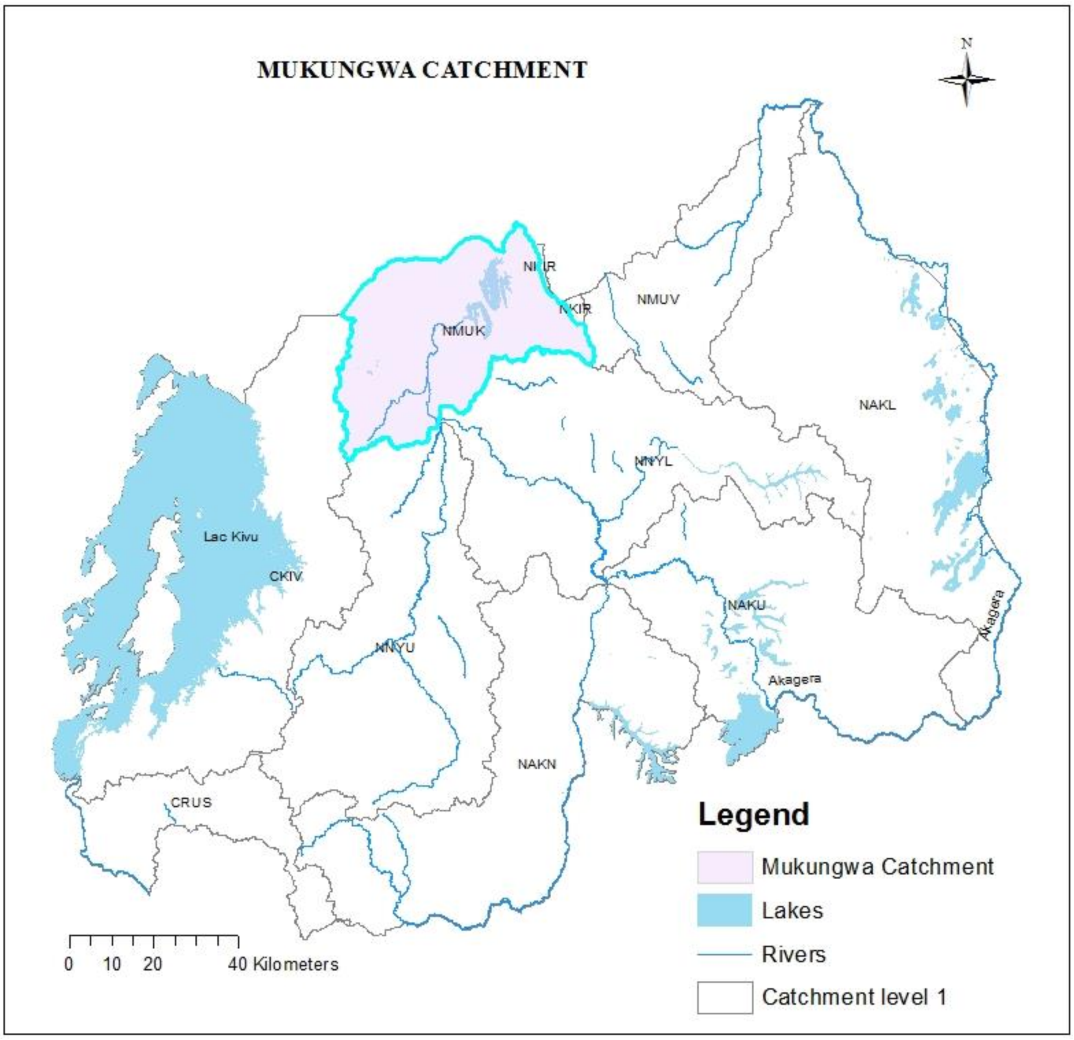

FIGURE 1: MUKUNGWA CATCHMENT MAP

1.2. Problem Statement

There are different competing water users and uses ranging from rural, urban, mining, irrigated agriculture, industry, power generation etc in Mukungwa catchment. The water resources of the catchment are limited and the demand is growing because of population growth, improvement in the standard of living of the population and socio-economic development taking place in the area. Some of the key water uses that are growing in the catchment include: existence of several natural reserves that demand special protection including having sufficient environmental flows in order to preserve the ecosystems, growth in the mining industry, development of new hydropower generation plants, and the revitalization of small scale irrigation schemes. All these developments in the catchment are resulting in increased water demand and competition for water use and making the supply and demand for water resources in the catchment is not well established. There is an information gap related to water availability and water demands in the Mukungwa catchment making it difficult for water resources planning such selecting water allocation scenarios and allocation limit for current and future uses. Therefore, there is a need to get a clear understanding of the total available renewable water resources in the catchment and plan for it appropriate allocation to the user for sustainable development and avoiding conflicts. This is especially important for the recently established Rwanda Water Resources Board (RWB) that is among others in charge of water resources management including allocation. Effective and efficient water resources management in Rwanda is critically important for the achievement of the targets of the Sustainable Development Goals embedded in the National Strategy for Transformation (NST I) of the country.

In addition to the above mentioned variable hydrology and the effect of climate change make it even more difficult to quantify the available water resources and manage it in a way that it could satisfy the increasing demands in the catchment. Having a clear understanding of available water resources as well as current and future demand is essential for planning to achieve sustainable development in the catchment. This work is intended to contribute to suitable water resources management through the application of modelling tools to assess current and future water availability and demands toward effective and efficient water resources management in Mukungwa Catchment.

1.3 Research objectives

The overall objective of this thesis is to contribute to sustainable water resources management in Rwanda through assessment of current and future water resources availability & demands and developing water allocation plan for Mukungwa catchment using WEAP model as a Decision Support System (DSS).

The specific objectives are the following:

1. To characterize the Mukungwa Catchment;
2. To develop and validate a conceptual water allocation and planning model using Water Evaluation and Planning (WEAP) model;
3. To develop proposal for current water allocation for the various water uses in the catchment (such as domestic, industrial, irrigation and environmental demands, etc.);
4. To assess current and future water availability in Mukungwa catchment;
5. To predict water demands and allocation and conduct water balance analysis for years 2030 and 2050 based on different development scenarios in the Mukungwa catchment;

1.4. Research Questions

1. What is the characterization of Mukungwa Catchment?
2. What will be the most suitable conceptual water allocation and planning model using WEAP model?
3. What will be the most suitable water allocation model for the various water uses in Mukungwa catchment?
4. What are the current and future water availability in Mukungwa catchment?
5. What are the possible development scenarios and what will be the water demands and appropriate allocation models under those scenarios in 2030 and in 2050?

1.5. Relevance and importance of this Thesis

Water managers and policy makers require tools in order to achieve a balance in water supply and demand, to ensure equitable allocation of water resources, protect the environment, promote efficient use of water and develop priorities in shared water resources. The application of a water permit system at Rwanda Water Resources Board (RWB) for any significant intervention in the natural hydrological cycle with the help of a well-established water allocation plan will further the aspired sustainability.

There is a need of characterizing the Catchment, to analyse the water balance of the Mukungwa catchment and to formulate water allocation plan for present and future demands. In order to implement the water allocation principles, consolidation of information, which shows the relationships between the water usage and water resources, is necessary. It is important firstly to understand the physical and managerial processes taking place at a catchment level and secondly to be able to predict the impacts of different future scenarios in order to start planning and managing today to solve the challenges and problems that will be expected tomorrow.

1.6 Scope and limitations of the study

The focus of the study was in the following aspects; the determination of the present water allocation for domestic, industrial, irrigation and environmental demands; the analysis of the water balance (supply and demand analysis) in the Mukungwa catchment; and the prediction of future water demands and allocation based on two development scenarios. The limitations of this study were mainly caused by Covid-19 pandemic prevention measures, which restricted some travels to the field and physical consultations. It was not easy to access all necessary data for this study. Insufficient financial means was also a major limitation, which resulted in the dependence on secondary data for some components of the study.

1.7. Structure of Thesis

This thesis is divided into five chapters, namely:

Chapter 1: This chapter presents the general introduction, the background of the study, the problem statement, the objectives, the research questions, relevance and importance of this Thesis, scope and limitations, and finally the report outline to highlight the structure of the thesis.

Chapter 2: This chapter presents mainly the literature review, which is focusing on previous similar studies done, water allocation principles and guidelines, WEAP model and different Decision Support System (DSS) tools for analysing water balance and allocation of water resources used by different researchers around the world.

Chapter 3: This chapter describes materials and methods used in this study, including characterization of the Mukungwa Catchment, conceptual water allocation and planning (WEAP) hydrology model setup, water allocation model (WEAP) overview for the various water uses, WEAP modelling process for current and future water availability, data requirements and collection, demand priorities and supply preferences, Model calibration and validation, and scenario development for 2030 and in 2050 projection.

Chapter 4: This chapter presents description of the findings of the study, such as Mukungwa Catchment characterization, water availability and water allocation for various water uses in the catchment for existing conditions, as well as water demands and water allocation under developed scenarios in 2030 and in 2050.

Chapter 5: The final chapter addresses conclusions based on the findings in relation to the research objectives and gives recommendations on the use of the findings and future research.

2. LITERATURE REVIEW

2.1. Introduction

Countries formulate water policies based on the principle of fair, reasonable and equitable usage. The primary aim of water policy is to sustainably manage and develop the available water resources. Proper planning, development and management of water resources are critical for meeting present and future water demands and avoiding potential water scarcity, crisis and conflicts (Sivakumar, 2011). Allocation of available water resources are undertaken objectively to ensure equity, environmental protection, development priorities, balancing supply and demands, and promote efficient use of water in response to scarcity due to unavailability and variability of water resources. Different models have been developed by researchers for allocating water resources between competing water users and for analysing the water balance of the river basins. WEAP is one of the water allocation models, which essentially follow a priority rule of allocation (Juizo D. and Liden E. , 2010) (Arranz R. and McCartney M, 2007). WEAP is a generic integrated water resource planning software tool that provides a comprehensive, flexible and user-friendly framework for the development of water balances, scenario generation, planning and policy analyses. It is commonly used in Rwanda for various catchment. Other models, such as MODSIM, MIKE BASIN, RIBASIM and REALM, are also commonly used for analysing the water balance of river basins and as decision support tools in water resource planning and management.

2.2. Water Management

2.2.1. IWRM Basic Principles

Integrated Water Resources Management (IWRM) is a participatory planning and implementation process, based on sound science that brings stakeholders together to determine how to meet society's long-term needs for water and coastal resources while maintaining essential ecological services and economic benefits. IWRM helps to protect the world's environment, foster economic growth and sustainable agricultural development, promote democratic participation in governance, and improve human health (ACC/ISGWR, 1992). Figure 2, show that how the IWRM is a participatory and coordinated process, it brings all water users together to emphasize social and economic welfare and equity and it is protecting the environment in trying to achieving equitable allocation of water resources.

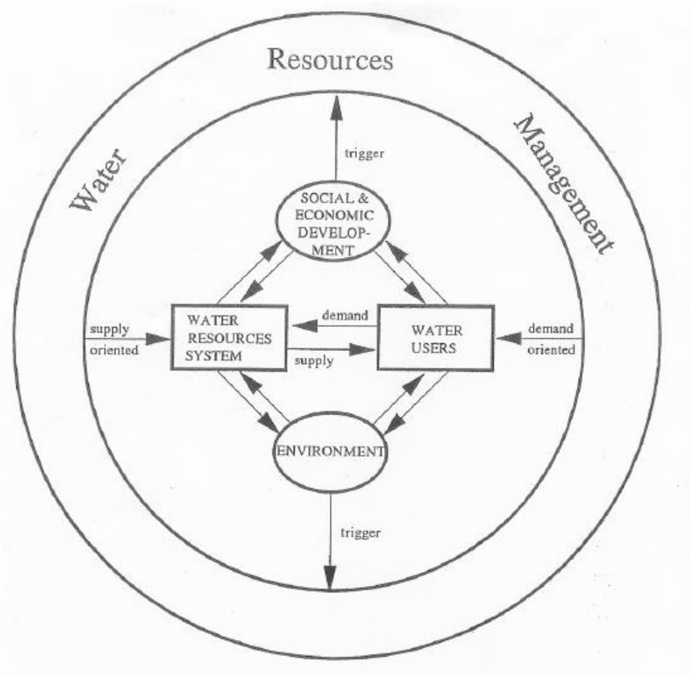

FIGURE 2: SCHEMATIC REPRESENTATION OF IWRM (ACC/ISGWR, 1992)

According to Global Water Partnership (2000), IWRM is defined as "a process, which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000).

Some of the principal components of IWRM are:

- **Managing water resources at the basin or watershed scale.** This includes integrating land and water, upstream and downstream, groundwater such as the western and eastern aquifer basins, surface water, and coastal resources;
- **Optimizing supply.** This involves conducting assessments of surface and groundwater supplies, analyzing water balances and evaluating the environmental impacts of distribution and use options;
- **Managing demand.** This includes adopting cost recovery policies, utilizing water-efficient technologies, and establishing decentralized water management authorities;
- **Providing equitable access to water resources through participatory and transparent governance and management.** This may include support for effective water users' associations, involvement of marginalized groups. This will happen at regulatory levels such as Rwanda Water Resources Board (RWB) level;
- **Establishing improved and integrated policy, regulatory, and institutional frameworks**;
- **Utilizing an inter-sectoral approach to decision-making,** where authority for managing water resources is employed responsibly and stakeholders have a share in the process.

2.2.2. Water Allocation Guidelines and Principles

Growing water demands for humankind, economic development and rise concerns placed on the environmental flow requirements intensify the need for proper allocation. Water allocation plans need to consider future scenarios, including changes in water availability, water use efficiency and water demands. Basin water allocation planning is typically to achieve equity among users, environmental protection, development priorities and balancing demands and supplies (Speed, 2013) .

Dinar et al., (1997) discussed four basic institutional mechanisms for water allocation: user-based allocation, Marginal Cost Pricing (MCP), public allocation and water markets allocation. User-based allocation requires collective action institutions with authority to make decisions on water rights and MCP sets a price for water equal to the marginal cost of supplying the last unit of that water. Public (administrative) allocation of water resources is broadly employed in countries where water is viewed as a public good and the governments allocate and distribute water permits as water use rights to users based on physical norms and political influence (Dinar A., Rosegrant M.W. and Meinzen-Dick R., 1997). Water markets have attractive potential benefits such as distributing secure water rights to users, providing incentives to use water efficiently and gain additional income through the sale of conserved water (Dinar A., Rosegrant M.W. and Meinzen-Dick R., 1997). The application of principles and approaches in water allocation also incorporates cooperation and negotiation between competing users (Wolf A., 2002). Cooperation is useful for transboundary negotiation because it provides a range of solutions, which will satisfy all users and provides methods to fairly and equitably allocate the resources (Teasley, 2009).

2.3. Water Resources Management Models for River Basin Simulation

Water resources management involves development, control, protection, regulation, and beneficial use of surface (rivers and reservoirs) and groundwater resources. Computer models play an important role in almost all aspects of water resources management including in the overall water resources management decision-making process (Wurbs, Ralph A., 2005). Computer-based Decision Support Systems (DSS) are useful tools for this because they allow the user to forecast and evaluate the impacts of different possible future trends and management strategies before implementing them (Mugatsia E.A., 2010).

In the following sections, several models commonly used for analysing the water balance of river basins/catchments and used as decision support tools in water resources planning and management are briefly discussed, showing its pros and cons, data requirement and its performances.

2.3.1. MODSIM

It is a simulation model that can be obtained free of charge. The model can simulate physical operation of reservoirs and water demand. The data sets can be developed for daily, weekly, and monthly time steps. It is generalized river basin decision support system and network flow model developed at Colorado State University designed to meet the growing demands and pressure on river basin manager. It has been linked with stream-aquifer models for analysis of the conjunctive use of groundwater and surface water resources, as well as water quality simulation models for assessing the effectiveness of pollution control strategies. It can be used with GIS for managing the intensive spatial data base requirements of river basin management. Results of the network optimization are presented in useful graphical plots. (http://modsim.engr.colostate.edu).

2.3.2. MIKE BASIN

MIKE BASIN was developed by the Danish Hydraulic Institute (DHI) in 2001. It is a mathematical representation of the river basin encompassing the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, existing as well as potential major schemes, and their various demands on water (DHI, 2003). It couples the ArcView and ArcGIS Geographic Information System (GIS) with hydrologic modelling to provide basin-scale solutions. The networks and nodes of the rivers are also edited in ArcView. MIKE BASIN can be used to determine quantity and quality of water in a river basin in a slowly changing system and is used as a DSS by investigating water sharing issues at international or interstate levels and between competing groups of water users, including the environment.

2.3.3. RIBASIM

The River Basin Simulation Model (RIBASIM) is a generic model package for simulating river basins under various hydrological conditions, (Ramadan et al., 2011). It was developed in 1985 at Deltares (formerly Delft Hydraulics) in the Netherlands. The model package is a comprehensive and flexible tool, which links the hydrological water inputs at various locations with the specific water-users in the basin. RIBASIM enables the user to evaluate a variety of measures related to infrastructure, operational and demand management and to see the results in terms of water quantity, water quality and flow composition. RIBASIM can also generate flow patterns, which provide a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs, (http://www.delta-alliance.nl/toolboxoverview/RIBASIM). RIBASIM has a set of features, which make it a state-of-the-art river basin simulation package. Water management organisations worldwide use it to support their management and planning activities.

2.3.4. REALM

The Resource Allocation Model (REALM) is a tool proven to aid in water resource planning and management in both urban and rural water supply systems and to represent the system network. It was developed in close collaboration with a diverse range of users in the water industry (George B., Malano H. and Davidson B. , 2008). REALM is a network allocation model based on a combination of water balance and a linear optimisation algorithm that enables the use of user-defined penalties and priorities to impose constraints and preferential resource use.

2.3.5. WEAP

Water Evaluation and Planning (WEAP) is a generic integrated water resource planning software tool that provides a comprehensive, flexible and user-friendly framework for the development of water balances, scenario generation, planning and policy analyses, (Dimova G., Tzanov E., Ninov Pl., Ribarova I. and Kossida M, 2013). It can be applied to municipal and agricultural systems, a single watershed or complex transboundary river basin systems. It was first formulated by the SEI in 1990 (Loon A.V. and Droogers P, 2006). WEAP simulates a broad range of natural and engineered components of these systems including rainfall runoff, base flow and groundwater recharge from precipitation, sectorial demand analyses, water conservation, water allocation priorities, reservoir operations, hydropower generation, pollution tracking and water quality, vulnerability assessments and ecosystem requirements. It also has an internal financial analysis module that allows the user to investigate cost-benefit implications for various management alternatives under different future scenarios. As a database, WEAP provides a system for maintaining water demand and supply information. As a forecasting tool, it simulates water demand, supply, flows and storage as well as pollution generation, treatment and discharge (SEI, 2015). As a policy analysis tool, it evaluates a full range of water development and management options and takes into account multiple and competing uses of water systems.

WEAP operates on the basic principles of balance between water supply and demand at various system nodes. It calculates a water and pollution mass balance for every node and link in the system on a monthly time step (Hao L., Huang L., Wang W. and Zhang H., 2011). The development of water balance through WEAP requires climate and hydrological data as well as data on water supply and demand in order to map the existing water resources and users within the basin and to allocate the abstraction and discharge of water. Water is allocated to meet in-stream and consumptive requirements, subject to demand priorities, supply preferences, mass balance and other constraints. Point loads of pollution into receiving bodies of water are computed and in-stream water quality concentrations are calculated (Yates D., Sieber J., Purkey D. and Lee A.H. , 2005).

WEAP operates on a monthly time step from the first month of the current accounts year through to the last month of the last scenario year. Each month is independent of the previous month, except for reservoir and aquifer storage. Thus, all of the water entering the system in a month (e.g. head flow, groundwater recharge or runoff into reaches) is either stored in an aquifer or reservoir or leaves the system by the end of the month (e.g. outflow from end of river, demand site consumption, reservoir or river reach evaporation, transmission and return flow link losses). Since the time scale is relatively long (one month), all flows are assumed to occur instantaneously. Thus, a demand site can withdraw water from the river, consume some, return the rest to a wastewater treatment plant that treats it and return it to the river. This return flow is available for use in the same month to downstream demands.

WEAP model generates also a flow-duration curve (FDC) of the river. FDC represents the relationship between the magnitude and frequency of water flow at different time steps, such as the daily, weekly and monthly stream flows for a particular river basin. The FDC thus provides an estimate of the percentage of time a given stream flow was equalled or exceeded over a historical period (Vogel R.M. and N. M. Fennessey., 1994). The streamflow record integrates the effects of climate, topography, and geology, and gives a distribution of runoff both in time and in magnitude (Searcy J.K., 1959).

Arranz and McCartney (2007) estimated the water balance and impacts of future water demands in the Olifants River Basin in South Africa using WEAP. Certain scenarios were considered to account for possible changes in the evolution of water demand: the implementation of the Environmental Reserve (ER), International Agreements (IAs), water conservation programmes and infrastructural development such as low, medium and high population growth (Arranz R. and McCartney M, 2007). For each scenario the unmet demands, stream flows and water storage was analysed using 1995 as the baseline. The outputs of the model showed that: (1) water shortages occurred during the 1995 baseline year and will occur in 2025; (2) the implementation of the ER allows more water flow in the rivers but less water is available to meet human demands; (3) the current storage capacity is less than the mean annual flow; (4) the construction of dams will help reconcile the water demands and resources; (5) the application of water conservation and demand management practices help to reconcile the water resources and demands but alone are not sufficient to satisfy all demands; and (6) the combination of new infrastructures and water conservation and demand management practices will enable a situation better than, or similar to, that of the 1995 baseline.

WEAP developed by the Stockholm Environment Institute in the early nineties, has been used worldwide in order to perform scenario analyses for water resources management. For instance, it has been used to assess the impacts of different water management practices in the Nyabugogo, Muvumba, Sebeya, Nyabarongo upper catchments, Akagera upper and Nyabarongo valley catchments in Rwanda.

3. MATERIALS AND METHODS

The Water Evaluation and Planning Model (WEAP) was used to build an IWRM model taking Mukungwa catchment as a case study. WEAP model is designed to support water planning that balances water supplies generated through catchment scale, physical hydrologic processes and multiple water demands and environmental requirements. The model deals with a varied range of issues that include climate, catchment conditions, water supply, ecosystem needs and anticipated demands.

3.1. Characterization of Mukungwa Catchment

3.1.1. Geography and location

The Mukungwa catchment geographical location was obtained from shapefiles collected in the datasets of Rwanda Water Resources Board, and processed using GIS software for producing a well-designed map as presented in the results section.

3.1.2. Land Use and Land Cover

Catchment Land Use and Land Cover (LULC) is an important component influencing hydrology and water resources characteristics in a given area. In this research, the 10-meter resolution GeoTIFF files from the Esri 2020 Land Cover map produced by Impact Observatory were used. The map is derived from ESA Sentinel-2 imagery and is a composite of land use/land cover predictions for 10 classes throughout the year in order to generate a representative snapshot of 2020 (Karra, 2021).

3.1.3. Topography

The topographic map of the catchment was produced using Digital Elevation Model (DEM) obtained from RWB database, which is at 10m resolution with the Geosurvey points of 2019.

3.1.4. Climate

The climate data were obtained from Meteo-Rwanda. The collected data includes rainfall, temperature, humidity and wind speed. These data were analysed and processed using state of the art Microsoft excel to get daily and monthly values, which in turn used in WEAP model hydrology.

3.1.5. Hydrology and water resources

The Mukungwa River flow was derived from the Ngaru-Mukungwa hydrological station, which is located at Mukungwa River before confluence with Nyabarongo River. Both river flow data and rivers shapefiles were collected from Rwanda Water Resources Board, then analysed and processed using GIS software and Microsoft Excel. Data and information related to wetlands were collected from datasets of Rwanda Environment Management Authority and consultations with REMA staff.

3.1.6. Population

The total population in the catchment was assessed based on the 2012 population census (1,048,631) and the growth rate of 2.6 by using a basic equation: $Nt = P\ e^{(r * t)}$. "Nt" represents the number of people at a future time; "P" is the population at the beginning time; "e" is the base of the natural logarithms (2.71828); "r" is the rate of increase (natural increase divided by 100); "t" represents the time period involved. The population density map in Mukungwa catchment was obtained using raster data published by Humanitarian Data Exchange (HDX) (https://data.humdata.org/dataset/0ee1affc-6a90-4ad3-b7eb-166645668fc3).

3.2. Conceptual water allocation and planning (WEAP) hydrology model setup

WEAP supports the use of three hydrologic modelling methods:

- Rainfall Runoff Method FAO (Food and Agriculture Organization of the United Nations),
- Irrigation Demands Only of FAO, and
- Soil Moisture Method.

The Soil Moisture Method (SMM) was selected to allow the most comprehensive analysis of characterization for land use and soil type. SMM is a one-dimensional, two soil layer algorithm for calculating evapotranspiration, surface runoff, sub-surface runoff and deep percolation for a defined land area unit, as represented in the figure 3 below. Table 1, gives an overview of different parameters that are important for the calibration of a WEAP model and their sensitivity.

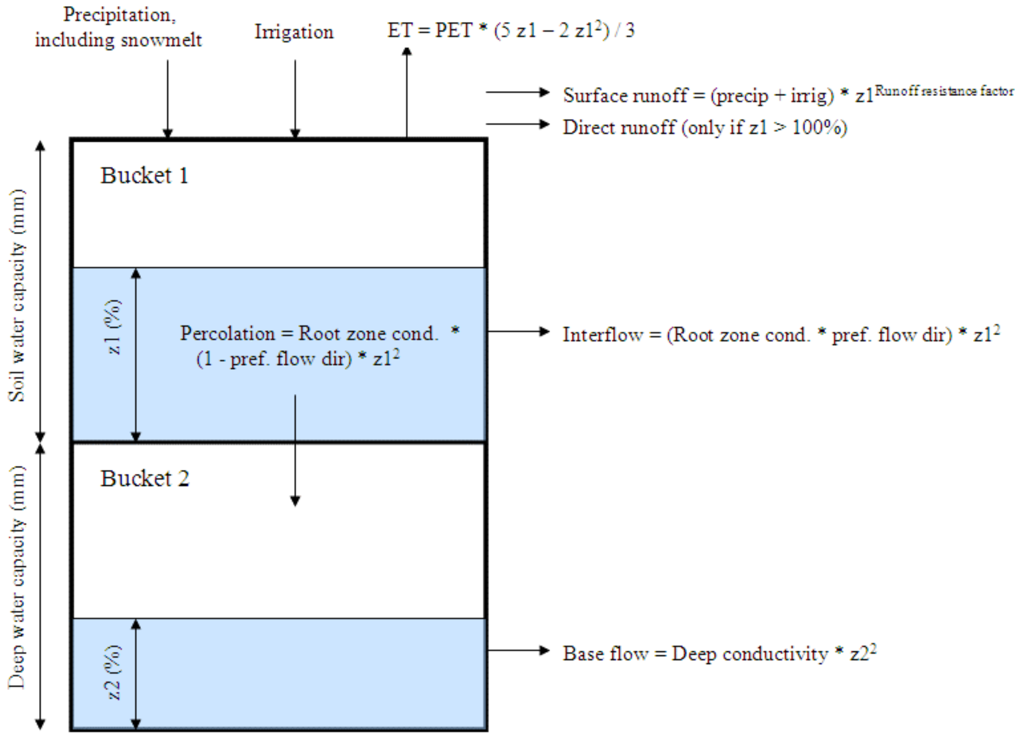

FIGURE 3: CONCEPTUAL WEAP HYDROLOGY MODEL (SEI, 2016)

TABLE 1: MAIN INPUT PARAMETERS AND SENSITIVITY (RWB, 2021)

Parameter	Units	Sensitivity	Remarks
Soil Water Capacity (SWC)	mm	Medium	• Effective water holding capacity to characterize soil groups within a sub-catchment. • Determines how much water can be stored in the soil. If SWC is high, more water can be stored which results in more (and more gradually) runoff and a higher ET.
Preferred Flow Direction (Pref. Dir)	no unit	Medium	• Used to partition the flow out of the root zone layer (top "bucket") between interflow and flow to the lower soil layer (bottom "bucket") or groundwater • > 0.5 is more interflow, <0.5 is more percolation.
Root Zone Conductivity (K_{sat})	mm/month	Medium	Root zone conductivity rate at full saturation (when relative storage z1 = 1.0), which will be partitioned, according to Preferred Flow Direction, between interflow and flow to the lower soil layer
Crop Coefficient, (K_c)	no unit	High	• Effects vegetative evapotranspiration and soil evapotranspiration. • Converts reference ET into potential ET
Runoff Resistance Factor (RRF)	no unit	Medium	• Used to control surface runoff response. Runoff will tend to decrease with higher values. • Impact minor when RRF > 10
Z1	%	Low	Z1 can only be set as an initial value, it will be calculated by WEAP. It gives the percentage of SWC that's filled with water. If Z1 is high, ETa will be high.

3.3. Water allocation model (WEAP) overview for the various water uses

WEAP is structured as a set of five different "views": Schematic, Data, Results, Scenario Explorer and Notes (Figure 4). These views are listed as graphical icons on the View Bar located on the left side of the screen. Schematic is GIS tool for configuring the system by dragging and dropping to create and position. Adding ArcView or other standard GIS vector or raster images as background layers. It is an instant access to data and results for any node. Data view is used to build Model. It creates variables and relationships, enter assumptions and projections using mathematical expressions, and dynamically link to Excel. Notes are views where data and assumptions are documented. Results view displays detailed model outputs in the form of charts, tables and maps. Scenario Explorer is high-level view of data and results.

The slider moves to change the value of the associated scenario data variable and WEAP recalculates so that the impact on user-selected key results are displayed.

The main menu at the top provides access to the most important functions of the program. A status bar is located at the bottom of the screen showing the current area name, current view, licensing information and other status information. The layout of the rest of the screen depends on which view is selected (SEI, 2016).

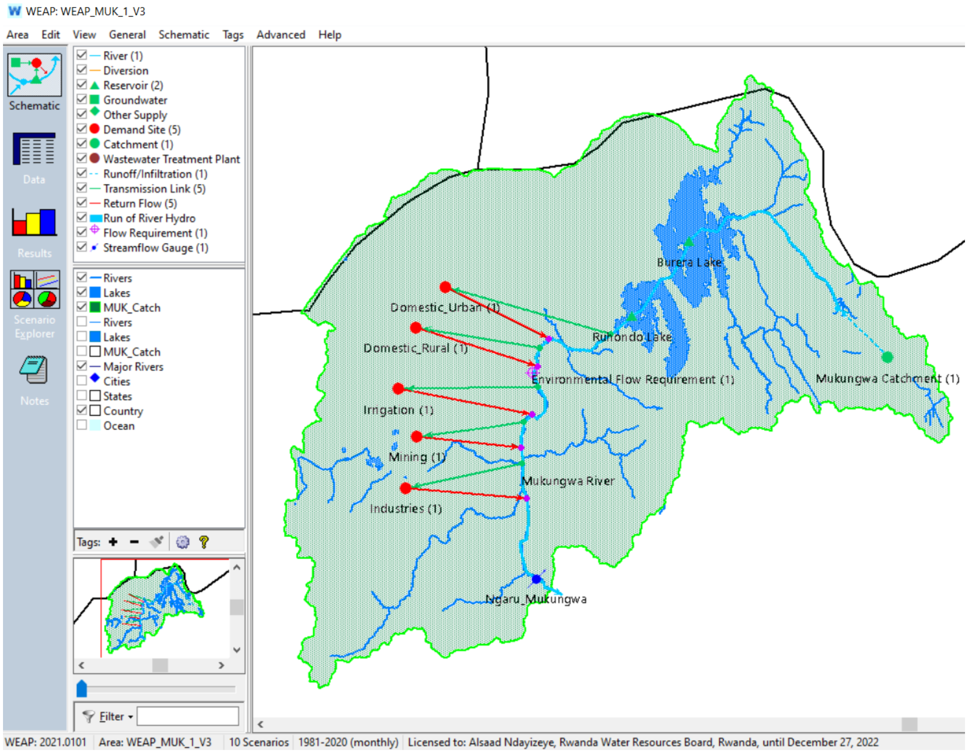

FIGURE 4: WEAP SCREEN VIEW, MENU BAR, AND SCHEMATIC VIEW THE MUKUNGWA CATCHMENT

3.4. WEAP modelling process for current and future water availability

For allowing simulation of water balance and water allocation, the elements that comprise the water demand-supply system and their spatial relationships were characterized for the Mukungwa catchment. The first point of the analysis is the development of catchment water demands. In WEAP Mukungwa modelling, the catchment comprises of five demand sites; domestic_urban demand site, domestic_rural demand site, irrigation demand site, industrial demand site, and mining demand site. Each demand site in the model is represented by a node and linked to the main river supply source. The environmental flow requirement (EFR) is not a water use sector. However, its impact on other water use sectors is evaluated depending on the volume of water allocated for EFR in the main river and its priority level in the modelling process, to provide water to ecosystems and downstream water users. The volume of water for EFR was set to a fixed 30 percent of the unimpaired flow.

Figure 5, illustrates the WEAP model framework for the simulation of water supply and use in the Mukungwa catchment.

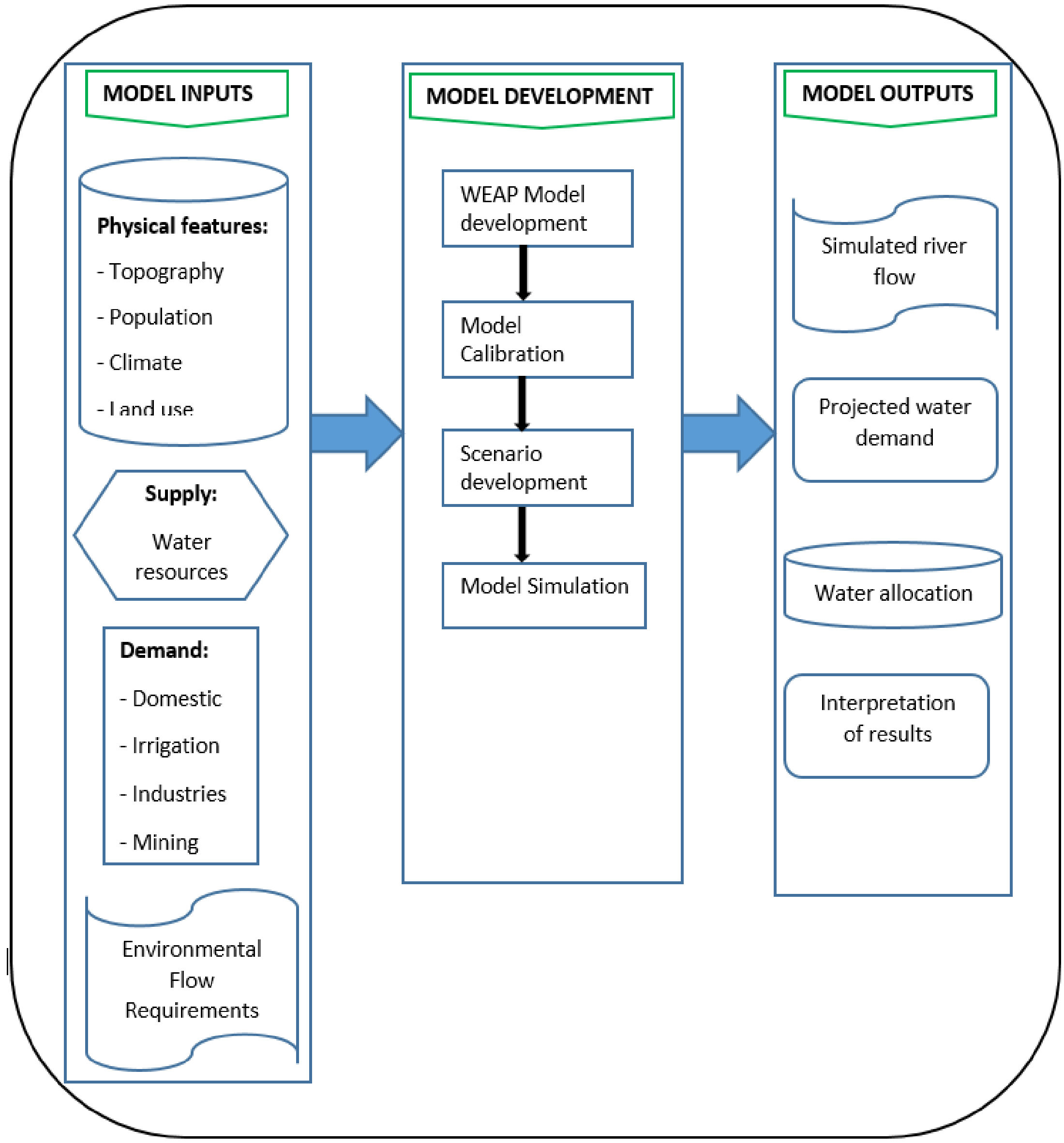

FIGURE 5: WEAP MODELLING FRAMEWORK

The process of modelling and simulation using WEAP in the catchment makes use of the following steps (Levite et al., 2003):

1. Problem definition including timeframe, spatial boundary, system components and configuration. This step involves setting area boundaries, mapping, problem identification and the collection of data. The required data is collected such as population, historical river flow, rainfall, catchment characteristics, present water supply, future development plan and standards and guidelines.

2. Establishing current accounts. The current accounts are viewed as a calibration step in the development of an application and they provide a snapshot of the actual water demand, resources and supplies for the system (Loon and Droogers, 2006). This forms the basis for the modelling process. In this study, the current account is set at 2020.

3. Building scenarios based on future assumptions. Scenario development forms the core of the WEAP model since this allows possible water resources management processes to be adopted from the results generated. The scenarios are used to address "what if" questions such as what if the current population growth changes? What if the EFRs are implemented?
4. Evaluating the water balance and allocation with respect to scenarios. The results generated from running the model are used as a DSS for decision makers.

3.5. Data requirements and collection

The data used in this study were obtained through site visits and from different sources, including Government Agencies, private companies, NGO's and different websites for published papers and books.

3.5.1. Population data and projection

The population data of the Mukungwa catchment were obtained from the National Institute of Statistics of Rwanda (NISR). A growth rate of 2.6% percent (NISR, 2012) was assumed for the entire catchment and the "GrowthFrom" function of the model was used to compute the future population for domestic demand site. The GrowthFrom function calculates a value in any given year using a growth rate from the Start Value in the Start Year as shown in the figure 6 below.

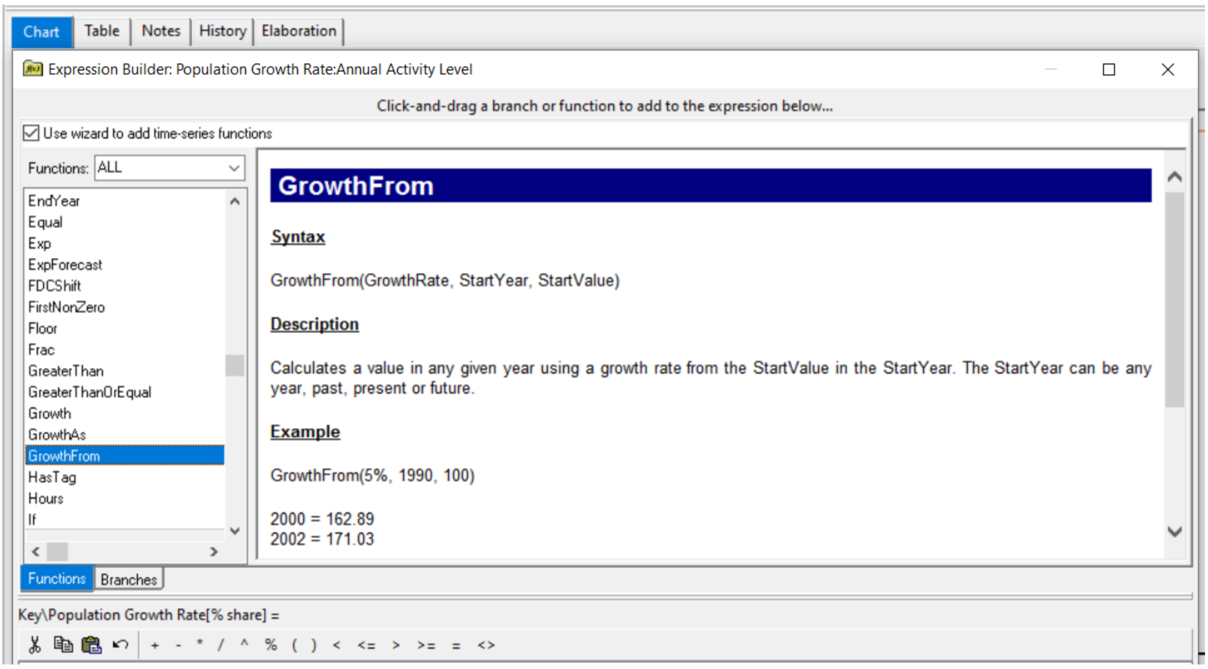

FIGURE 6: SCREENSHOT OF WEAP MODEL FUNCTION FOR POPULATION PROJECTION

3.5.2. Hydrometeorology

The precipitation data sets were collected from Rwanda Meteorology Agency (Meteo-Rwanda) include the following:

- Station based measurements to represent long-term trends in precipitation, and
- Grid based data sets to represent spatial changes in precipitation within the catchments. The grid data sets are specifically important to evaluate impacts of geographical conditions on the amount of rainfall.

The grid database of Meteo-Rwanda covers the entire catchment with a time span for precipitation between 1 January 1998 to 31 December 2018 while maximum and minimum temperatures are available between 1 January 1983 to 30 June 2017 as shown in the table 2.

For the WEAP model, additional climate data are needed to estimate the potential evapotranspiration as screenshotted in the figure 7. For relative humidity and wind speed, the average monthly data for Ruhengeri station have been used.

TABLE 2: CLIMATIC DATA

Months	Precipitation (mm)	Temperature (°C)	Humidity (%)
January	68.8	10.64	77
February	133.6	10.74	77
March	157	10.44	79
April	166.9	10.14	83
May	86.8	10.44	80
June	37.6	10.74	69
July	8.8	11.04	60
August	57.8	11.74	60
September	107	11.14	69
October	126.3	10.64	76
November	168.9	9.94	81
December	95.4	10.14	79

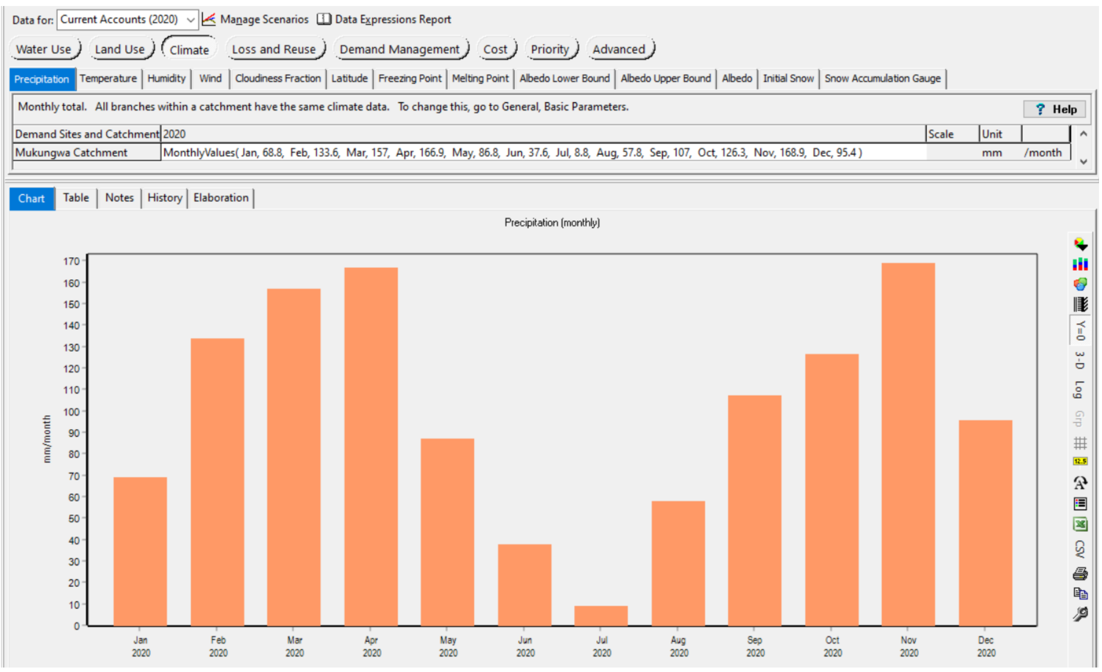

FIGURE 7: SCREENSHOT OF WEAP INPUT DATA (PRECIPITATION IN MM/MONTH)

3.5.3. Soil data

Soil data is essential for the development of WEAP models, which uses a typical bucket model concept, often used in hydrological modelling that is based on land use classification. Each land use type needs its own parameterization. Soil data required for the schematization of a WEAP model includes:

- Root zone conductivity (mm/month)
- Soil Water Capacity of the root zone (storage capacity) (mm)
- Runoff Resistance Factor (controls surface runoff) (unit less)
- Preferred Flow Direction (controls flow out of the root zone layer between interflow and groundwater) (unit less)

The table 3 gives an overview of the different soil parameters for the different land use classes.

Table 3: Soil parametrization of the hydrological WEAP model (Droogers, 2017)

No.	Land use Class	Root zone conductivity (mm/month)	Soil Water Capacity (mm)	Runoff Resistance Factor (unitless)	Preferred Flow Direction (unitless)
1	Forest	500	10000	500	0.1
2	Open areas or grass	200	2000	200	0.5
3	Agriculture (Seasonal)	260	2000	10	0.7
4	Settlements and Buildings	10	200	1	1
5	Water	-	-	-	
6	Wetlands	300	10000	500	0.8
7	Sparse Forest	260	5000	500	0.1
8	Agriculture (Perenial)	260	2000	10	0.7
9	Marshland	150	5000	10	0.8

3.5.4. Water Demand

Water demand analysis in WEAP is a disaggregated, end-use based approach for modeling the requirements for water consumption in an area. Using WEAP you can apply economic, demographic and water-use information to construct alternative scenarios that examine how total and disaggregated consumption of water evolve over time in all sectors of the economy. Demand analysis in WEAP is also the starting point for conducting integrated water resources planning analysis, since all Supply and Resource calculations in WEAP are driven by the levels of final demand calculated in the demand analysis.

WEAP provides a lot of flexibility in how you structure your data. These can range from highly disaggregated end-use oriented structures to highly aggregate analyses. Typically, a structure would consist of sectors including households, industry and agriculture, each of which might be broken down into different subsectors, end-uses and water-using devices. You can adapt the structure of the data to your purposes, based on the availability of data, the types of analyses you want to conduct, and your unit preferences. Note also that you can create different levels of disaggregation in each demand site and sector (Sieber, 2015).

The water demand in Mukungwa catchment was assessed for existing and future conditions in the following sectors:

- Domestic
- Industrial
- Irrigation
- Mining
- Environment flow requirement

The sectoral water demand values for existing and future conditions are driven by data sets collected from the national institutions, and the corresponding assumptions to represent both the existing and future conditions (2030 and 2050).

3.5.4.1. Domestic water demand

Domestic water demand was calculated by using population (both urban and rural), and water demand (both urban and rural) at the administrative-sector scale as per the following conditions:

a) Population in administrative sectors: existing conditions (2020) reflect the medium-growth conditions of NISR census data of 2012.

b) Population in catchment scale: aggregation was applied in reference to surface areas of administrative sectors within the catchment area.

c) Water demand of urban and rural populations (in l/person/day) in 2020 and 2050 were adopted from planning figures of WASAC Ltd as well as National Water Resources Master plan (NWRMP); which is 100 l/p/d for urban and 60 l/p/d for rural in 2020; while in 2030 and 2050, water demand is expected to be 120 l/p/d for urban and 100 l/c/d for rural population;

d) The corresponding urban and rural water demand in 2020 and 2050 are summarized in the table 4 below.

TABLE 4: WATER DEMAND FOR URBAN AND RURAL (2020 AND 2050)

2020		2030 and 2050	
Urban (l/p/d)	Rural (l/p/d)	Urban (l/p/d)	Rural (l/p/d)
100	60	120	100

3.5.4.2. Industrial water demand

The reference data on industries was collected from:

- The Ministry of Trade and Industries (MINICOM);

- The department of agriculture and natural resources, department of business development and employment and investment offices of corresponding administrative districts; and
- The Rwanda Water Resources Board (RWB), on the current industries water use.

The projections of future demand for industries were calculated by using an annual industrial growth rate of 13% for the period covering the National Strategy for Transformation (NST1, 2017-2024). According to the Rwanda vision 2050, industrial sector is expected to contribute to 33% of GDP by 2050.

Despite the pyrethrum, iron sheet and cement factories found in Musanze District and the Tea and Dairy Factories in Nyabihu District, other factories are small-scale industries processing food such as banana wine, milk, irish potatoes, juice and ginger processing units, with low consumption of water. The tea and dairy factories are the two main consumers of water in Nyabihu District as their consumption ranges between 935 and 1,250 m^3/month, respectively. The water demands and projections in Mukungwa catchment are presented in the table 5 below.

TABLE 5: INDUSTRIAL WATER DEMAND (IN M3)

Year	2020	2030	2050
Water use (m^3)	49,879	49,879	107,868

3.5.4.3. Irrigation water demand

Irrigated agriculture is not yet commonly present in Mukungwa catchment, as the area characterized by high rainfall satisfying crop water requirement in main crop seasons. In total, the current surface irrigation of marshland is about 1,711 Ha, mainly present in the eastern part of the catchment. The irrigation water demand is estimated at 6,066 m^3/ha/year based on the crop water requirement published in Irrigation Master Plan of 2020, with most of the demand required between May and September. The Irrigation Master Plan indicates that the gross water demand of marshland areas ranges roughly between 6,000 m^3/ha/y (Food and horticulture) and 18,000 m^3/ha/y (Paddy). For hillside irrigation, the gross water demand ranges roughly between 6000 and 8000 m^3/ha/y. The figure 8 highligts the existing and potential irrigation areas.

As per the database of Irrigation Master Plan, the irrigation areas are presented in the table 6, through:

- Existing sites for irrigation assumed to represent 2020;
- Full potential sites for irrigation to represent 2030 and 2050.

It is important to note that rainfed areas are excluded from the irrigation areas.

TABLE 6: IRRIGATION AREAS (EXISTING AND FUTURE CONDITIONS)

Existing Irrigation Sites (ha)	**Potential sites for Irrigation (ha)**	
	2030	**2050**
1,711	491	3,436

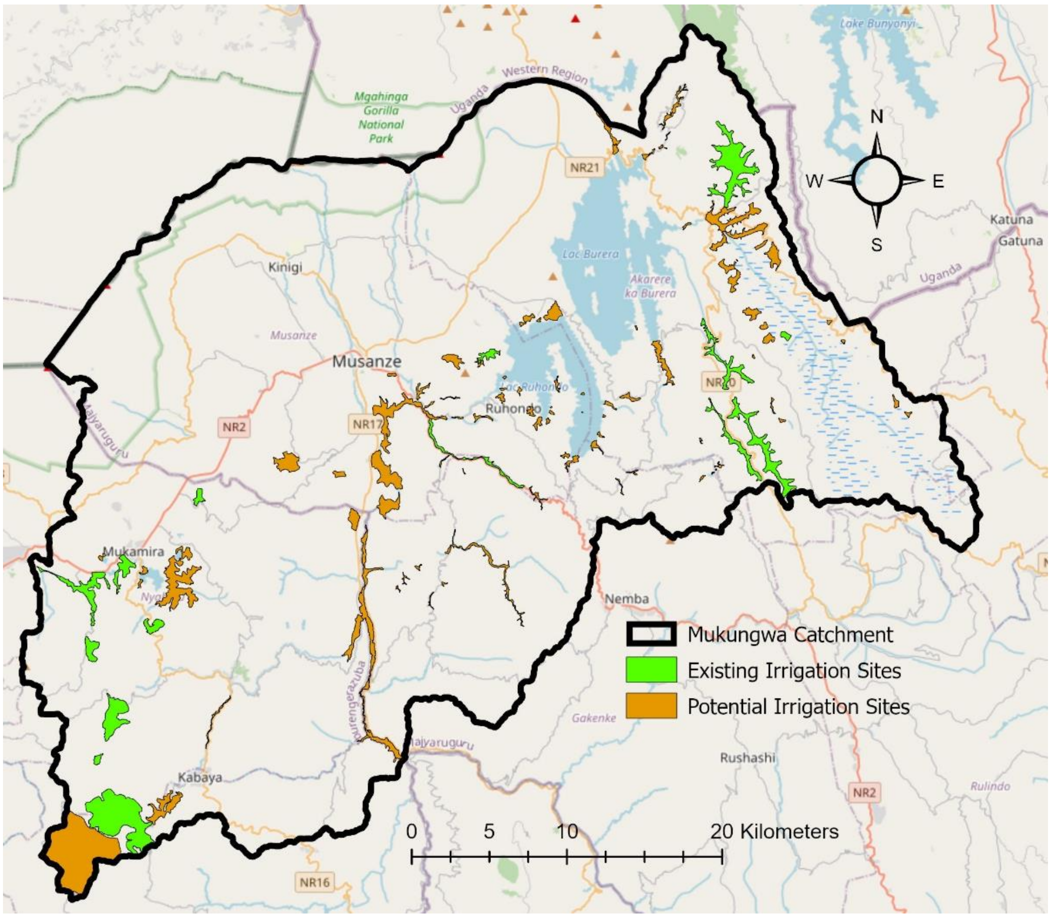

FIGURE 8: EXISTING AND POTENTIAL IRRIGATION MAP

3.5.4.4. Mining water demand

Current water demands from mining activities were collected from the database of Rwanda Water Resources Board (RWB, 2020) as well as consultation with Rwanda Mining, Petrolium and Gas Board (RMB) Staff. The projections on water demands were calculated based on export figures of the major three exported minerals, i.e. cassiterite, colta and Wolfram as indicated by the National Bank of Rwanda. The annual growth rate was calculated for each individual mineral and an average was computed for the three minerals for the period between 2012-2020. Then a total growth rate of 12% was assumed for every 10-year period. The corresponding estimated for existing and future projections are summarized in the table 7.

TABLE 7: MINING WATER DEMAND (IN MCM/YEAR)

Year	2020	2030	2050
Water demand (m^3)	520,000	590,000	750,000

3.5.4.5. Hydropower Plants water demand

The data on existing hydropower plants was obtained from the Rwanda Energy Group (REG), which includes, design flow and installed capacity of the HPP. The electricity demand is forecasted to increase on an annual growth rate of 10% in reference to the Rwanda Least Cost

Power Development Plan (LCPDC)-2019-2040 for the country. HPP generation is assumed to follow the same trend. The main characteristics of 16 existing HPPs are presented in the table 8. It is important to note that the water use in hydropower return back in the river system downstream of the powerhouse. However, any water abstraction in the upstream of the hydropower site, affect the power generation. This calls much attention in the water allocation to other consumptive water use.

TABLE 8: EXISTING HYDROPOWER PLANTS IN MUKUNGWA CATCHMENT

Name of HPP	Capacity (MW)	Start year	Average production (kwh/yr)	Flow (m^3/s)
Mukungwa 1	12.0	2011	54414848	14.00
Mukungwa 2	3.6	2013	9243263	13.60
Rwaza	2.6	2018	10341335	12.00
Mutobo	0.2	2014	874141	-
Kigasa	0.3	2020	452521	-
Ntaruka	11.3	2011	27477016	12.00
Rugezi	2.6	2011	5860458	-
Giciye 1	4.0	2014	11792476	4.00
Giciye 2	4.0	2016	12505550	4.00
Giciye 3	9.8	2020	2789640	4.00
Rubagabaga	0.5	2019	798698	0.89
Nyamyotsi 1	0.1	2014	7226	-
Nyamyotsi 2	0.1	2014	24991	-
Gaseke	0.5	2017	1077083	2.30
Musarara	0.4	2013	2397467	-
Janja	0.2	2014	138191	0.34

3.5.4.6. Environmental Flow Requirements

The in stream flow requirements are set to a fixed 30 percent of the unimpaired flow, consistent with the Rwanda National Water Resources Master Plan (RNRA, 2015). The unimpaired flow was calculated under baseline scenario, representing the hydrology without water storage, and then imposed as an environmental flow requirement in WEAP.

3.6. Demand Priorities and Supply Preferences

The Demand Priority represents the level of priority for allocation of constrained resources among multiple demand sites. WEAP attempts to supply all demand sites with highest Demand Priority, then moving to lower priority sites until all of the demand is met or all of the resources are used, whichever happens first. Priorities can range from 1 to 99, with 1 being the highest priority and 99 the lowest.

A demand priority can be any whole number between 1 and 99 (1 is the default) and allows the user to specify the order in which the water requirements of demand sites are satisfied. WEAP will attempt to satisfy the water requirement of a demand site with a demand priority of 1 before a demand site with a demand priority of 2 or greater. If two demand sites have the same priority, WEAP will attempt to satisfy their water requirements equally. Absolute values have no significance for the priority levels; only the relative order matters.

Demand priorities allow the user to represent in WEAP water allocation as it actually occurs in their system. For example, a downstream industry may have historical water rights to river water, even though another demand site positioned upstream could extract as much river water as it desired, leaving the industry with little water in the absence of such water rights. The Demand Priority setting allows the user to set the industry's priority for water above that of the upstream demand site. Demand Priorities can also change with time or change in a scenario.

The Supply Preference parameter allows you to define which source should be used in priority to supply water to the demand site. WEAP will attempt to supply all of the demand with sources having the highest preference level, only using lower-level sources if the high-level sources do not have sufficient supply.

In reference to the Water Law N°49/2018 of 13/08/2018 determining the use and management of water resources in Rwanda (Rwanda, 2018); the domestic demands have given the high priority, followed by environmental flow requirement, then industrial and irrigation demands.

3.7. Mukungwa WEAP Model Calibration and Validation

Calibration is the adjustment of model parameters, so that the model reproduces the observed prototype data at an acceptable accuracy. The WEAP model calibration involves the quantitative evaluation of the hydrologic response of the catchment with the aim of fitting the simulated data to the observed flow data obtained from gauging stations.

WEAP includes a linkage to a parameter estimation tool (PEST) that allows the user to automate the process of comparing WEAP outputs to historical observations and modifying model parameters to improve its accuracy. In this study, PEST Calibration was used to help calibrate one or more variables in WEAP model, which can be particularly useful when using the Soil Moisture method of catchment hydrology. Calibration can be also done using sensitivity analysis for soil parameters.

The model calibration can be done by using a variety of data sources including but not limited to river flow data, evapotranspiration data, precipitation data, etc. Since the measured flow data are limited, and available flow data are highly affected by upstream hydropower operations; the calibration was done using the following data sources:

- WaPOR remote sensing based evapotranspiration data, to calibrate actual evapotranspiration within the time period available between 2009 and 2020.
- Climate input data such as precipitation data.

The calibration of WEAP hydrology model was done through the following steps:

- Compare annual average observed precipitation from Meteo-Rwanda;

- Compare modelled annual actual evapotranspiration (Eta) values against WaPOR for an acceptable margin of +/- 5%.

It is important to highlight that average annual evapotranspiration of the WEAP model is almost the same as WaPOR evapotranspiration. The annual actual ET from WaPOR versus ET from WEAP is presented in the figure 9. The average annual difference is approximately -2% with very similar patterns between the two.

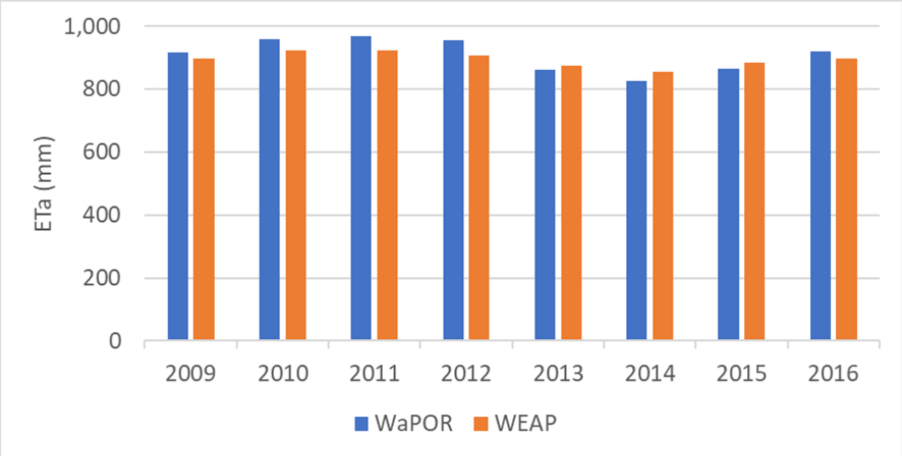

FIGURE 9: ANNUAL ACTUAL ET FROM WAPOR VS ET FROM WEAP FOR MUKUNGWA CATCHMENT

The stream flow data was also analyzed as summarized below:

- Calculated runoff or stream flow (red line) for Ngaru_Mukungwa hydrological station is slightly lower compared to the observed mean runoff or stream flow (blue line) from the figure 10;
- It is important to note that this irregularities in observed data, caused by the upstream hydropower operations at Burera and Ruhondo Lakes.

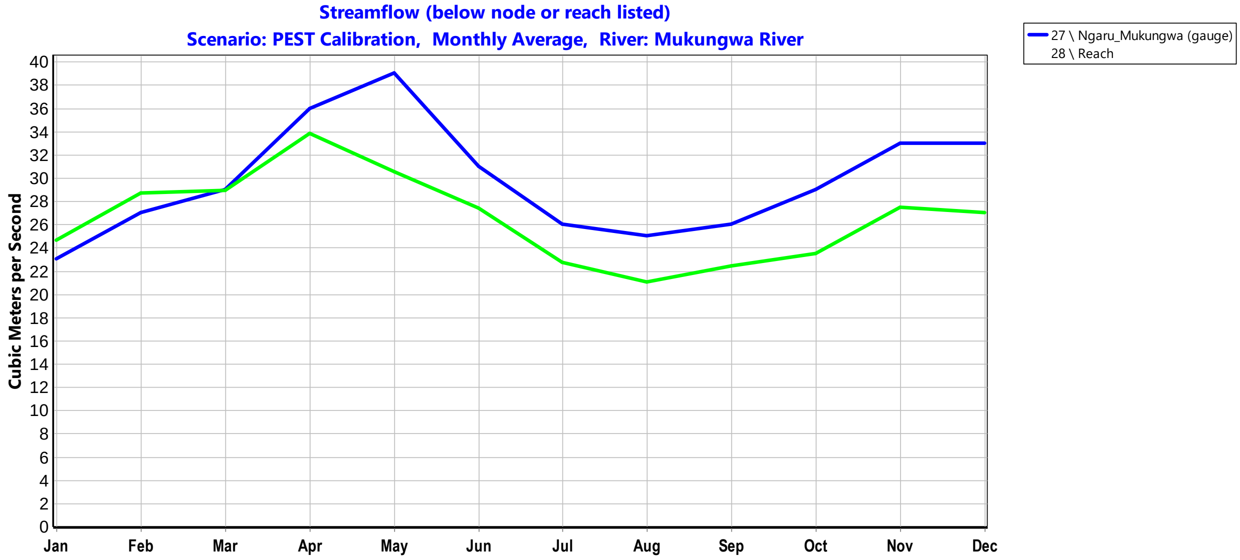

FIGURE 10: OBSERVED VS CALCULATED STREAM FLOW AT NGARU_MUKUNGWA HYDROLOGICAL STATION.

3.8. Scenario development for 2030 and in 2050 projection

At the heart of WEAP is the concept of scenario analysis. Scenarios are self-consistent story lines of how a future system might evolve over time in a particular socio-economic setting and under a particular set of policy and technology conditions (Sieber, 2015). Using WEAP, scenarios can be built and then compared to assess their water requirements, costs and environmental impacts.

Scenarios in WEAP encompass any factor that can change over time, including those factors that may change because of particular policy interventions, and those that reflect different socioeconomic assumptions. Sensitivity analyses may also be done by varying uncertain factors through their range of plausible values and comparing the results. These scenarios may be viewed simultaneously in the results for easy comparison of their effects on the water system.

In order to address a broad range of "what if" questions, three projection scenarios (2030 and 2050) were developed and their possible impacts on the catchment water balance evaluated.

- Scenario 1 considers an increase in population growth rate (increased population generates increased water demand);
- Scenario 2 considers an increase in economic development (sectoral water demands such as increase in irrigated areas, in industry and manufacturing, in mining, etc.);
- Scenario 3 deals with the implementation of an environmental flow requirement (ecosystems and downstream water demand).

Following these three sectoral scenarios, the combination of both has been analysed and reported. The details on each projection scenario was discussed in the section presented above.

4. RESULTS AND DISCUSSION

This chapter describes the Mukungwa Catchment, and the results calculated by the Mukungwa WEAP model. The results include baseline/reference and future projections scenarios for 2030 and 2050 results. The results reflect the outcomes of water availability, water demand, water balance, and resulting unmet demand in Mukungwa catchment.

4.1. Mukungwa Catchment characterization

4.1.1. Geography and location

The Mukungwa catchment is one of the nine Catchment Management Areas existing in Rwanda (figure 11). It covers Districts of Musanze and Burera as well as partly of Nyabihu, Gakenke and Ngororero Districts. It comprises a large zone with tuff and lava deposits sloping downward from a series of five towering volcanoes characterized by rather thinly distributed, partly ephemeral and discontinuous surface channels interacting with very complex and intricate Ground water flows in the north-west. The East of the catchment features steep hills that drain onto a spectacular cascading system of high altitude wetland (Rugezi) and lakes (Burera and Ruhondo) from which the Mukungwa River emerges in the centre of the catchment. It has a catchment area of around 1,900 km² (of which 119 km² is reserved area in the volcano park).

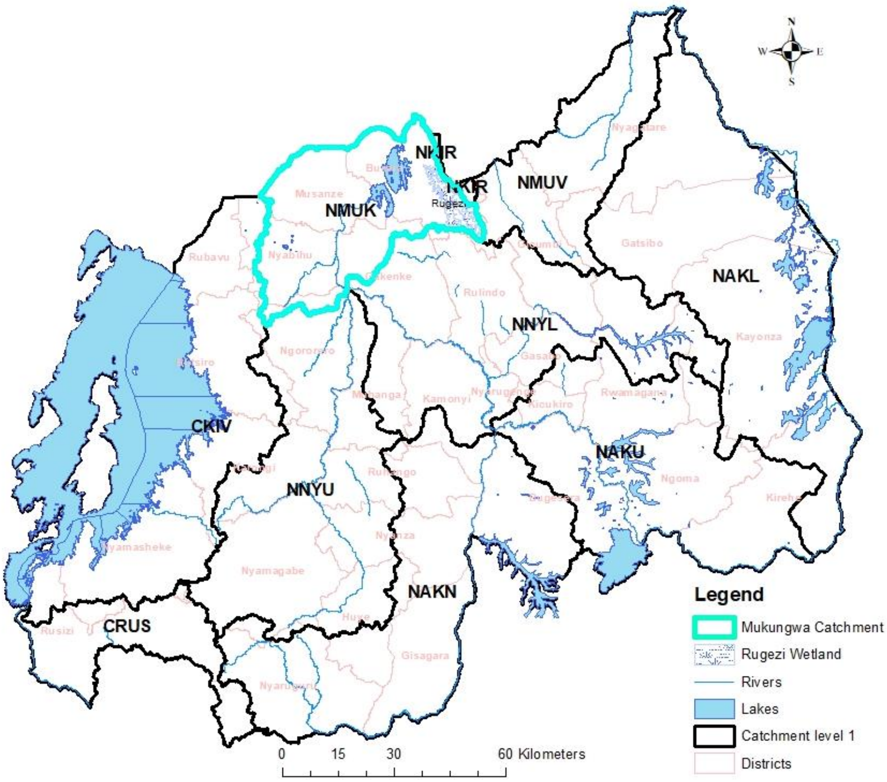

FIGURE 11: MUKUNGWA CATCHMENT LOCATION

4.1.2. Land Use and Land Cover

The land cover in Mukungwa Catchment is mainly made of cropland (approximately 44% of total), built area (approximately 20% of total) and forest (approximately 18% of total). The wetlands and lakes mostly cover the most eastern part of the catchment as shown in the figure 12. The table 9 provides summary of land cover classes in the catchment.

TABLE 9: SUMMARY OF LAND COVER CLASSES IN MUKUNGWA CATCHMENT

Land Cover	Area (Ha)	Percentage (%)
Water	8,784.76	4.80
Forest/Trees	33,503.90	18.30
Grass	8,376.78	4.58
Flooded vegetation	444.18	0.24
Crops	80,920.12	44.20
Shrub	13,434.64	7.34
Built Area	36,680.73	20.04
Bare ground	64.78	0.04
Clouds	854.34	0.47
Total	183,064.24	100

Land Cover Class definitions:

Water

Areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.

Trees

Any significant clustering of tall (~15m or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense tall vegetation within savannas, plantations, swamp or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).

Grass

Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures.

Flooded vegetation

Areas of any type of vegetation with obvious intermixing of water throughout a majority of the year; seasonally flooded area that is a mix of grass/shrub/trees/bare ground; examples: flooded mangroves, emergent vegetation, rice paddies and other heavily irrigated and inundated agriculture.

Crops

Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land.

Shrub

Mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs and tufts of grass, savannas with very sparse grasses, trees or other plants.

Built Area

Human made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings and residential housing; examples: houses, dense villages / towns / cities, paved roads, asphalt.

Bare ground

Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation; examples: exposed rock or soil, desert and sand dunes, dry salt flats/pans, dried lake beds, mines.

Clouds

No land cover information due to persistent cloud cover.

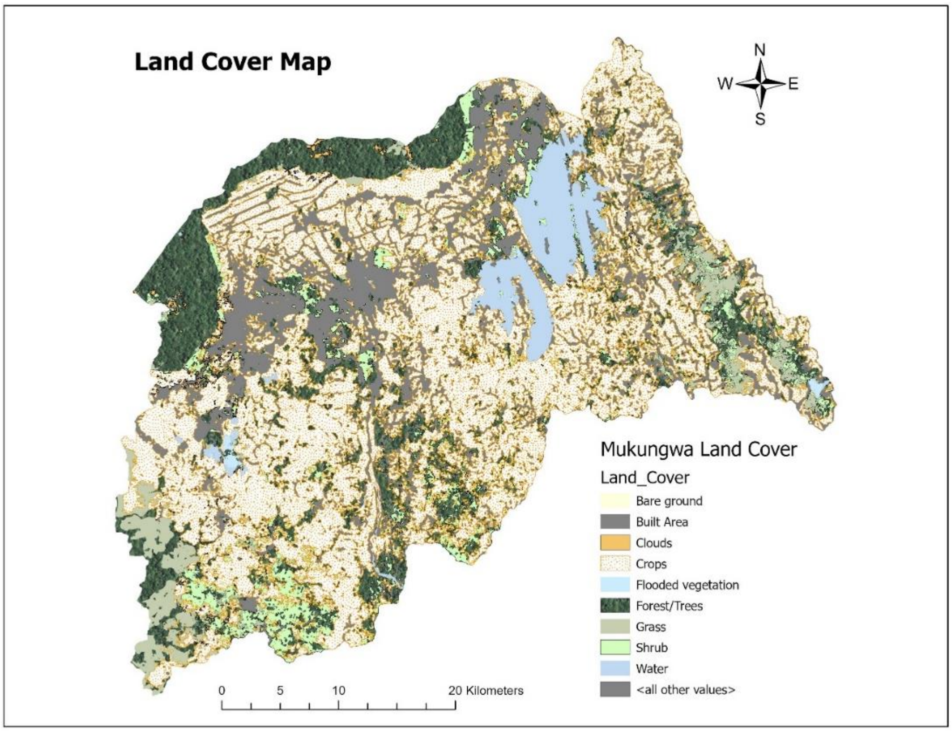

FIGURE 12: LAND COVER MAP OF MUKUNGWA CATCHMENT

4.1.3. Topography

Mukungwa catchment is characterised by steep slops and high elevation ranging from 1398 to 4130 masl as shown in the figure 13.

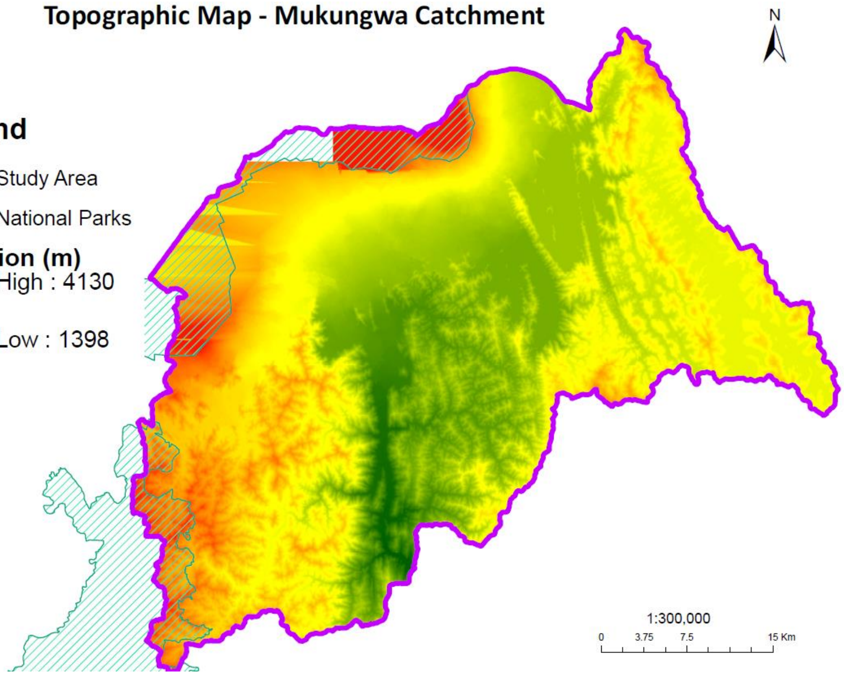

FIGURE 13: MUKUNGWA CATCHMENT TOPOGRAPHIC MAP

4.1.4. Climate

Rwanda has a tropical climate characterized by its hilly landscape stretching from east to west. The country has four primary climatic regions: eastern plains, central plateau, highlands where Mukungwa catchment is located, and regions around Lake Kivu. The eastern plains receive an annual rainfall of between 700 mm and 1,100 mm, with mean annual temperature oscillating between 20°C and 22°C. The central plateau region enjoys rainfall of between 1,100 mm and 1,300 mm, with an annual mean temperature of between 18°C and 20°C. The highlands, including the Congo-Nile Ridge and volcanic chains of Birunga, benefit from an annual rainfall of between 1,300 mm and 1,600 mm and experience annual mean temperatures between 10°C and 18°C. Regions around Lake Kivu and Bugarama plains get annual rainfall of between 1,200 mm and 1,500 mm with annual mean temperatures between 18℃ and 22℃. Annual precipitation is 1,170.2 mm. Rainfall is experienced throughout the year in Rwanda, with most significant rainfall occurring from September to May. (https://climateknowledgeportal.worldbank.org/country/rwanda/climate-data-historical). The figure 14 shows the annual rainfall in Rwanda for different regions.

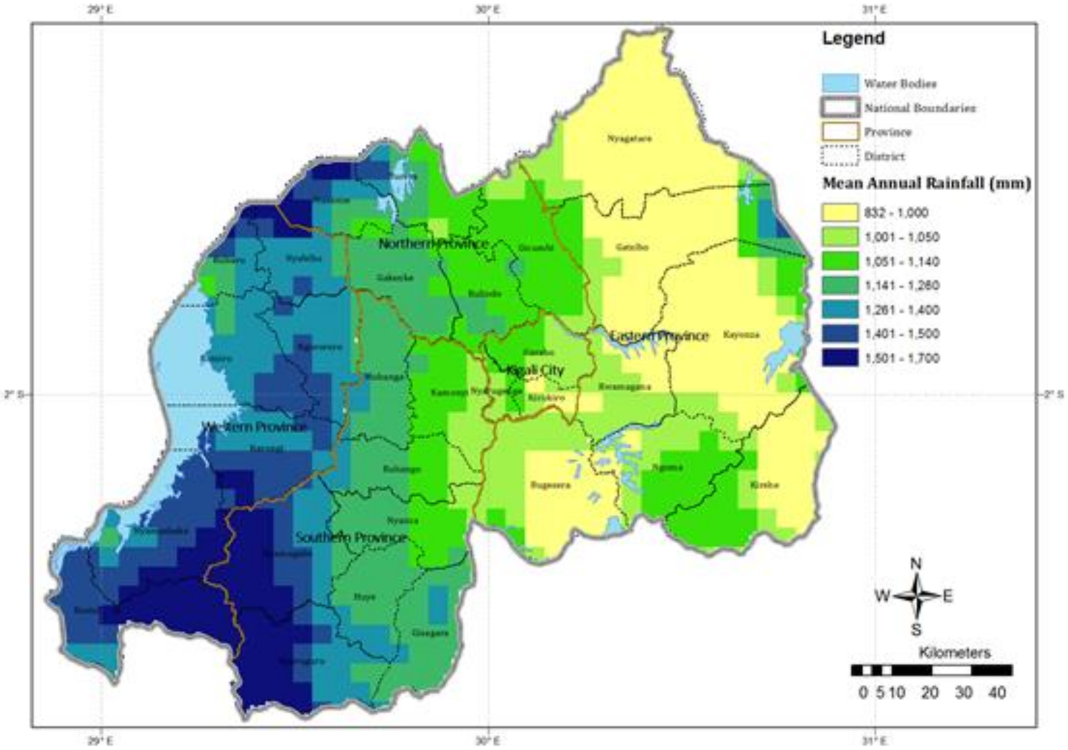

FIGURE 14: MEAN ANNUAL RAINFALL IN RWANDA (source: meteo-rwanda)

Temperature

- Average monthly temperature in Mukungwa catchment ranges between 9.94℃ to 11.74℃ as shown in the figure 15.

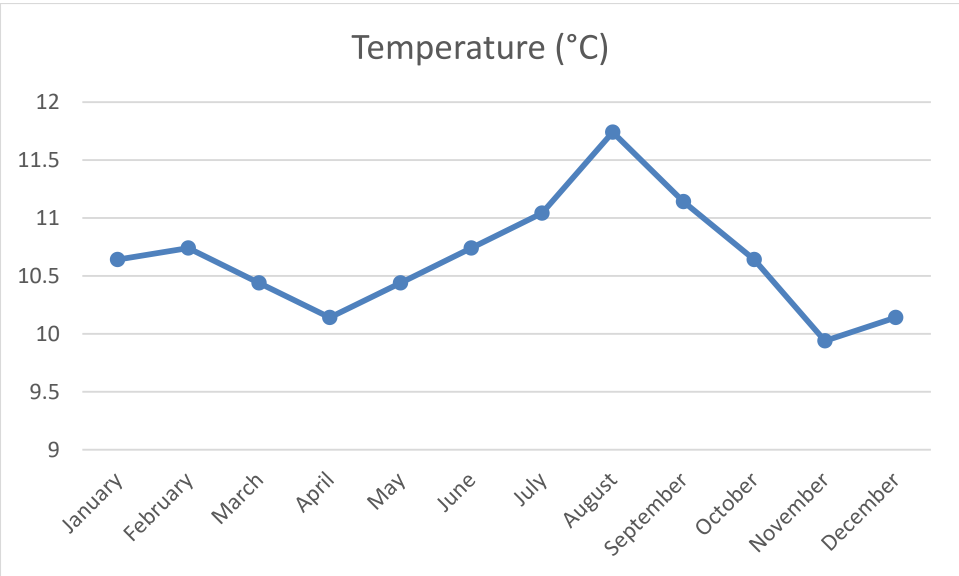

FIGURE 15: AVERAGE MONTHLY TEMPERATURE IN MUKUNGWA CATCHMENT

Precipitation

- Rainfall trends have shown an increasing occurrence of extremes since the 1960's across various regions of the country with the El Niño Southern Oscillation influences precipitation trends during El Niño years.

- The annual rainfalls in Rwanda exhibited high fluctuations since 1961 to 2016. Over this period, mean rainfall significantly decreased in January, February, May and June, but with a significant increase September to December across the country.
- In the northern and western provinces where Mukungwa catchment is located, rainy seasons are becoming shorter and more intense, which has resulted in increased erosion risk and floods in these mountainous areas of the country.
- Average monthly precipitation in Mukungwa catchment ranges between 8.8mm to 168.9mm as shown in the figure 16.

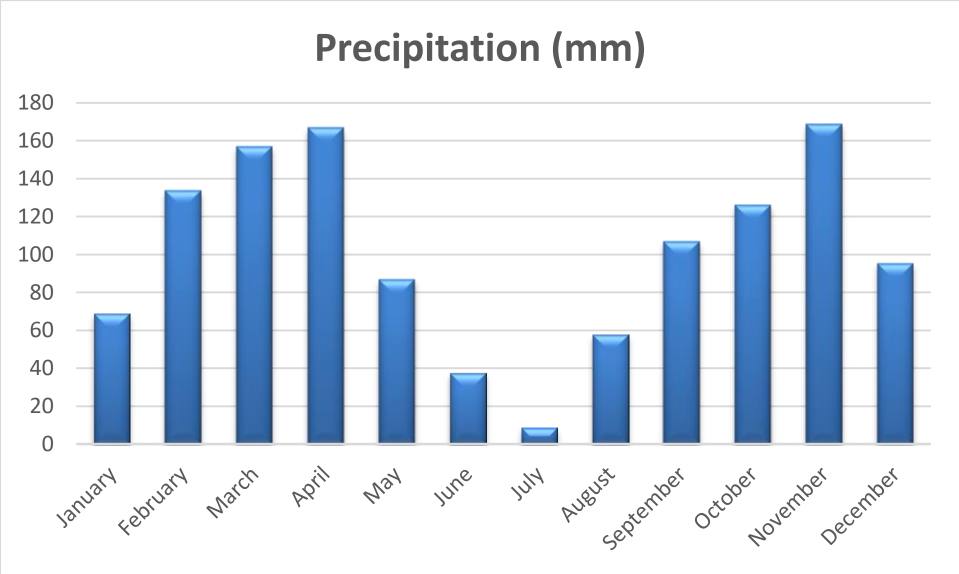

FIGURE 16: AVERAGE MONTHLY PRECIPITATION IN MUKUNGWA CATCHMENT

4.1.5. Soil

Mukungwa catchment's soils are dominated by deeply weathered, well-drained, erodible, fertile tropical soils and dark surface layer soils with a high infiltration capacity originating from volcanic materials. They are dominated by andosols in the north and west, Cambisol in the Centre, East and south and a mix of Nitisol-Acrisol-Alisol-Lixisol in the south. Small pockets of Histosols occur in the south and east, and a small area of Ferralsol occurs in the mid-west of the catchment. The figure 17 shows the soil map of the catchment.

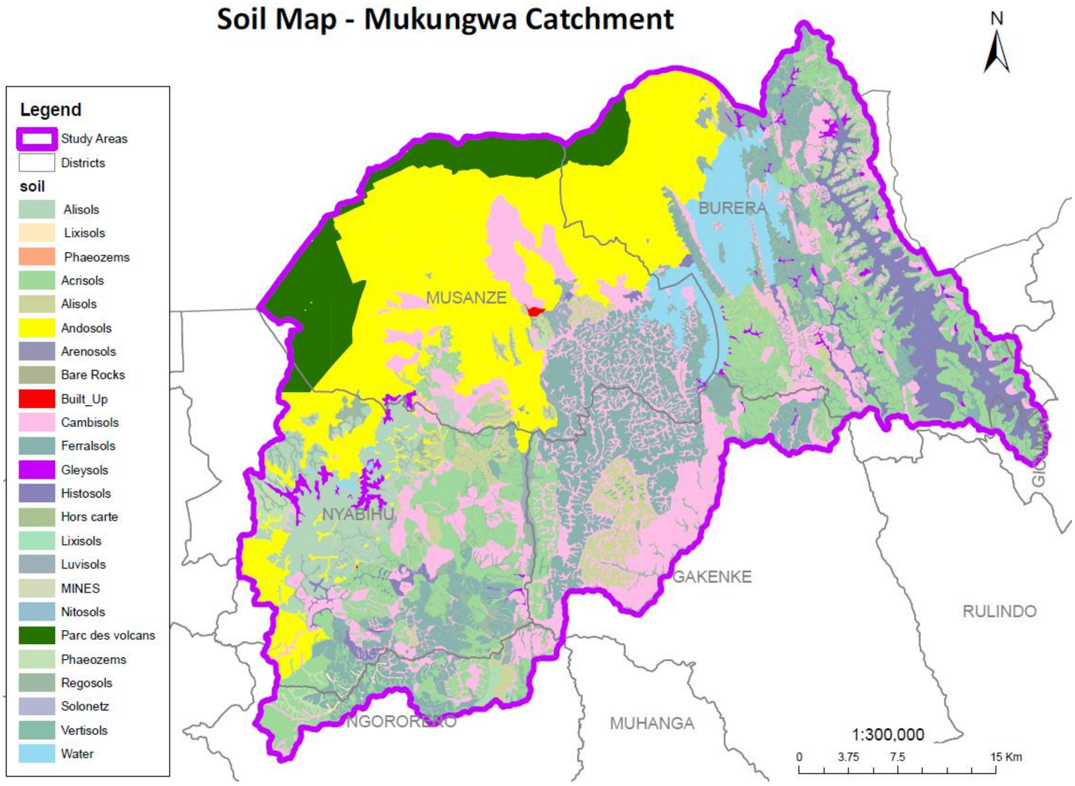

FIGURE 17: MUKUNGWA CATCHMENT SOIL MAP (RWB, 2021)

4.1.6. Hydrology and water resources

The hydrological response to rainfall within a catchment is determined largely by land morphology. The Mukungwa catchment is a mountainous area with high elevation. Surface water flows are sustained during the dry season (July and August) and there is a very restrained hydrological response during the short rainy season (September to December), when infiltration to ground waters significantly reduces direct runoff. During the long rainy season (February to May), monthly flows show a greater increase, indicating that groundwater reserves are completely replenished at this time. The instantaneous peak flow levels in this period are often significantly higher than the monthly average flow levels. This happens when the infiltration capacity of the soil is not sufficient to absorb heavy rain. Due to deforestation in favour of agriculture and urbanisation, infiltration capacity has decreased over time and surface runoff (and related soil erosion) has increased. The average annual rainfall is slightly above 1,315 mm/annum, which equates to some 2,563 hm^3/annum.

In seasons with moderate rainfall intensities, significant infiltration occurs, leading to storage within groundwater aquifers along the main rivers and its tributaries. High infiltration rates, combined with deeply weathered groundwater holding layers, result in significant groundwater reserves that effectively regulate surface flows. Unfortunately, such groundwater reserves are difficult to access directly for large abstractions. The figure 18 shows the catchment main rivers, wetlands and lakes.

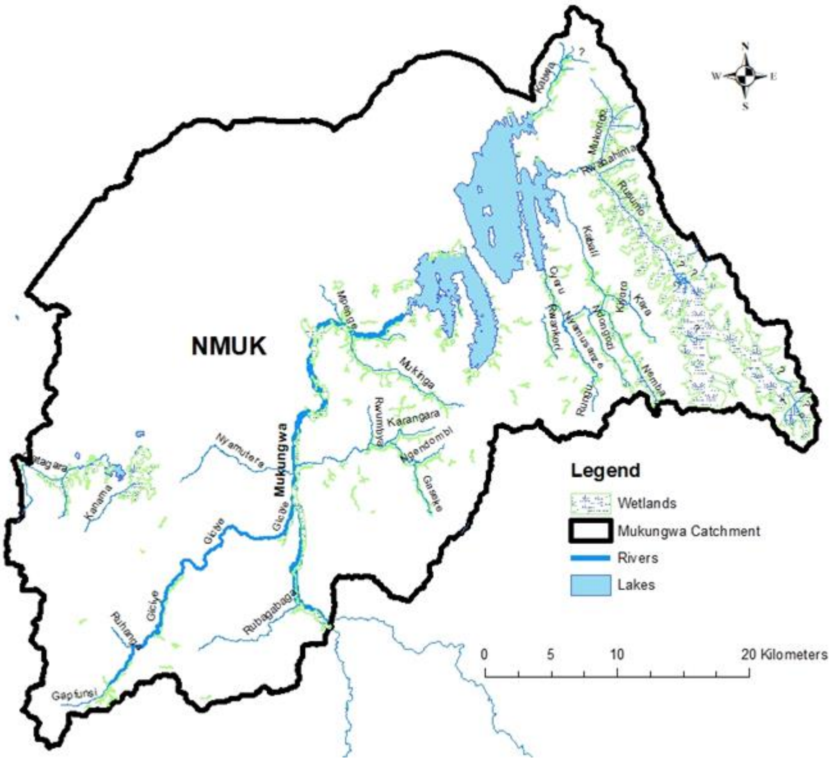

FIGURE 18: MUKUNGWA CATCHMENT HYDROLOGY MAP

The monthly distribution of discharge of Mukungwa River is presented in the figure 19 below.

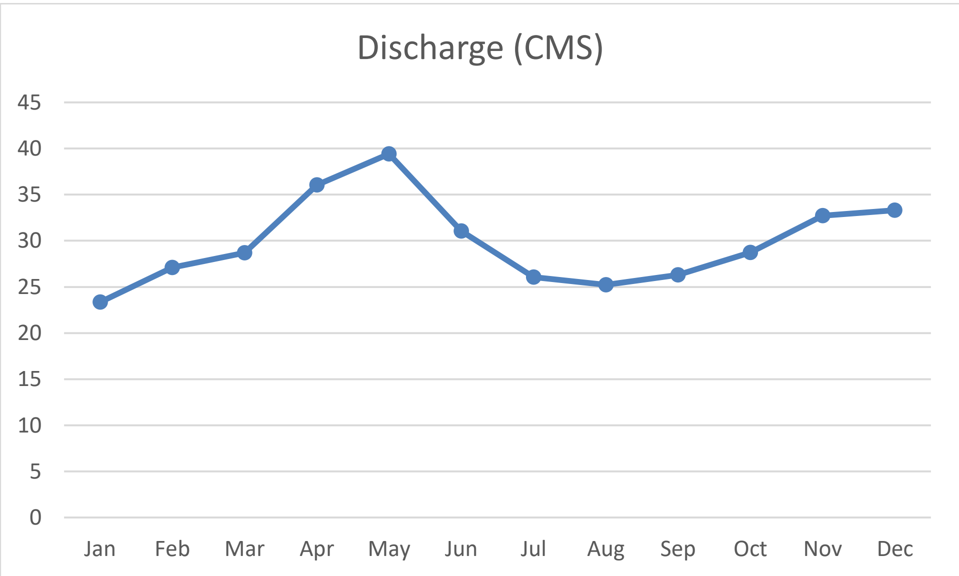

FIGURE 19: MONTHLY AVERAGE DISCHARGE OF MUKUNGWA RIVER

Wetlands

Some of the important functions of wetlands include; sediment and nutrient removal of surface waters; carbon sequestration; provision of habitat for wildlife; and flow augmentation by retaining ground and surface water in the soil and vegetation. It is important to note that some of the wetlands have the risk of losing their ecosystem services due to the scale of impacts on the stream flow conditions. A variety of conditions including reduction of vegetation cover has also reduced sediment retention and flood control and has led to a gradual erosion of biodiversity (REMA, 2009). The sustainability of wetland systems is specifically important in Rwanda with total of 935 wetlands covering a total area of 176,337 ha, as gazetted in the Prime Minister's Order No 006/03 of 30/01/2017.

There are 55 wetlands in Mukungwa catchment with a total area of 15,267 ha. Some of the well-recognized wetlands in Mukungwa include Rugezi Marshland (International RAMSAR site), Karago Lake, Gatungati-Rubagambavu-Rusumo-Rugezi complex, Burera and Ruhondo Lakes, Mukungwa Marshland, Nyamukongoro-Gatagara complex and Nyirabirandi wetland.

4.1.7. Population

The total catchment population in 2020 is about 1,291,088 dispersed throughout the catchment with highest densities in and around the urban Centres of Musanze and along the Musanze – Rubavu national road as shown in the figure 20. The Mukungwa catchment is the highest densely populated in Rwanda.

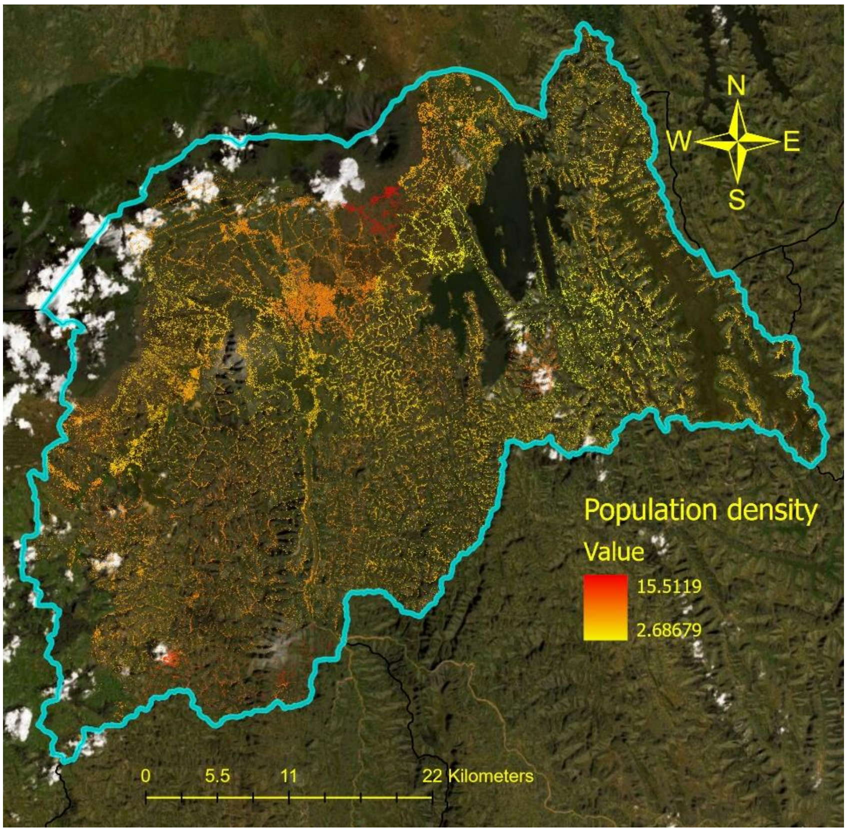

FIGURE 20: POPULATION DENSITY MAP OF MUKUNGWA CATCHMENT (HOUSEHOLDS PER HA)

4.1.8. Socio-economic characteristics

The economy of the Mukungwa catchment relies strongly on rain-fed agriculture, both for rural livelihoods and exports. Horticulture is common in the catchment as the fertile soils in the area lead to high production levels of e.g. vegetables and Irish potato. Mining, both commercial and artisanal, is common and 'sand mining' in riverbeds is also an important economic activity in the downstream sections of the Giciye River and other tributaries.

Sand mining has the dual benefit of producing a high-quality construction material that is much in demand, as an economic benefit, and of helping to maintain flow capacity of the river. The complicating factor is that the mined sand derives from upstream mining activities and soil erosion, which themselves have adverse impacts on the catchment as well as the suitability and usability of river water for water supply and hydropower.

With regard to other economic activities, Volcanoes National Park is the main source of foreign currency from tourism activities, commercial activities, fisheries development in Burera and Ruhondo Lakes.

The Volcanoes National Park helps in maintaining biodiversity and nature conservation (including mountain gorillas and many interesting animals species), as well as in increasing tourism revenues.

Mukungwa catchment contains different main rivers, including Mukungwa, Mukinga, Mutobo, Giciye, Rubagabaga, Gaseke Rivers, etc, as well as Rugezi wetland (Ramsar Site) and twin lakes of Burera and Ruhondo. These rivers and lakes are the source of water for large number of Hydropower Plants, supplying electricity to the whole country. The catchment includes the district capital of Musanze, which is one of the secondary cities of Rwanda with increasing demands for water and electricity.

There is a significant increase of rural grouped settlements, which facilitates the provision of basic services such as WASH services, electricity, schools, healthcare, etc. A very small percentage, urban dwellers only, have house water connections; the remainder only have access to an unprotected spring or a river as their only (unimproved) source of water supply (RWB, 2021).

4.2. Water availability and water allocation for various water uses in Mukungwa catchment - Baseline or Existing conditions

The results for the baseline condition are discussed in the following sections. The results were calculated under the current climate, current water demand for the various sectors and existing irrigated areas.

4.2.1. Water availability and Reliability

The total water availability in the Mukungwa catchment is estimated at 883.4 MCM annually, unevenly distributed in months. This includes surface runoff from the catchment area, base flow, and return flows. As the catchment is located in the upstream part of the Nile basin, there is no inflows entering the catchment. The annual outflow from the catchment to the downstream catchments was assessed at Mukungwa River outlet, which is estimated at 835.5 MCM and unevenly distributed in months. The figure 21 shows the Mukungwa River flow, which is the major river receiving all tributaries of the Mukungwa catchment. It is clear that the river flow is high during rainy season, and reduces during dry season. It can be seen from the figure that the minimum flow occurs in the month of August and peak flows occur in the month of April.

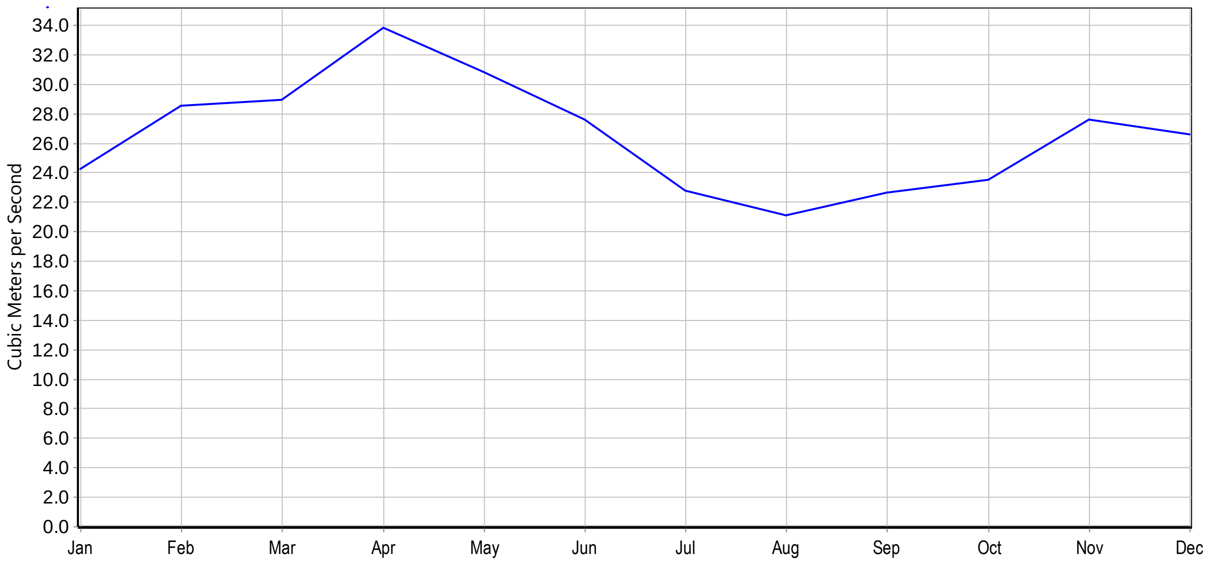

FIGURE 21: MONTHLY STREAM FLOW OF MUKUNGWA RIVER AT OUTLET.

The water reliability was assessed using a flow-duration curve of the Mukungwa catchment using WEAP model. When the flows are arranged according to frequency of occurrence and a flow-duration curve is plotted, the resulting curve indicates how much flow is available for abstraction based on the time equal to or exceeding the dependable flow. This kind of information is very useful for hydropower design and operations.

The figure 22 below shows the flow duration curve of Mukungwa River in the catchment, which indicates the availability of water on the time equal to or exceeding the dependable flow.

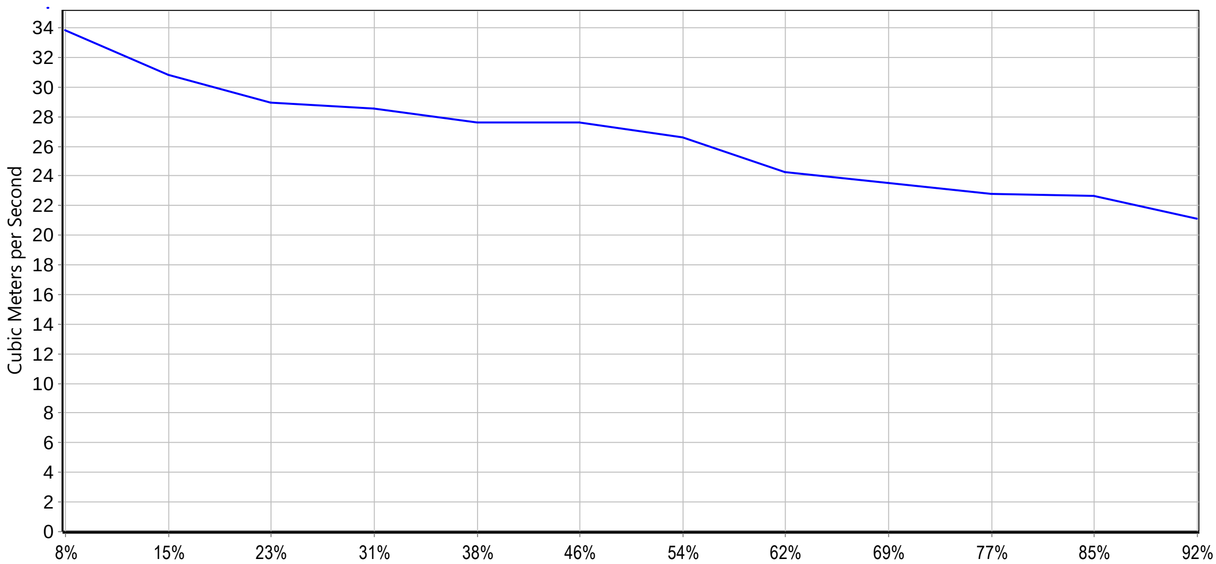

FIGURE 22: FLOW DURATION CURVE FOR MUKUNGWA RIVER

4.2.2. Water Demand

WEAP model calculated monthly domestic both urban and rural areas, irrigation and industries water demands during baseline year (2020). The results show that domestic is the largest water use sector, which comprises of 66% of total water demands equivalent to 31.7 Mm^3, followed by irrigation with 22% of total water demands equivalent to 10.4 Mm^3.

The table 10 below presents the WEAP model results in Mukungwa catchment, where the total annual water demand is about 48 Mm^3. The figure 23 shows the monthly water demand for all demand sectors.

TABLE 10: WATER DEMAND FOR ALL SECTORS IN (TCM OR 1000M3)

Demand sector	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**
Domestic	2,688	2,449	2,688	2,601	2,688	2,601	2,688	2,688	2,601	2,688	2,601	2,688	**31,667**
Industries	8	8	8	8	8	8	8	8	8	8	8	8	**100**
Irrigation	519	-	-	-	1,038	2,076	2,595	2,076	1,038	-	519	519	**10,379**
Mining	485	442	485	470	485	470	485	485	470	485	470	485	**5,720**
Sum	**3,701**	**2,899**	**3,182**	**3,079**	**4,220**	**5,155**	**5,776**	**5,257**	**4,117**	**3,182**	**3,598**	**3,701**	**47,866**

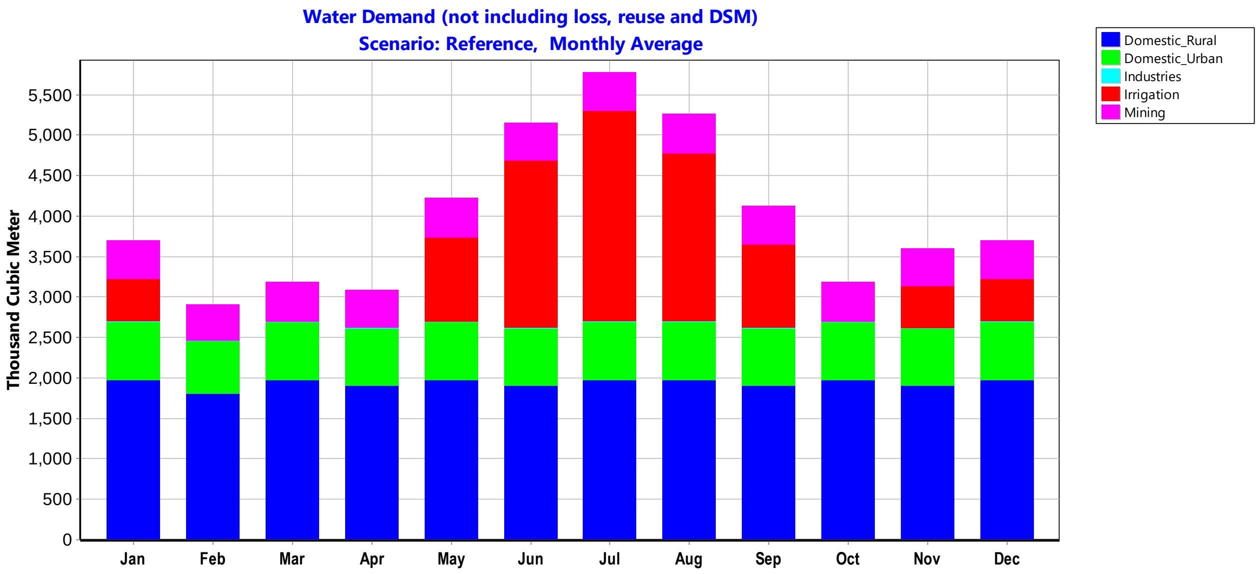

FIGURE 23: MONTHLY WATER DEMAND FOR ALL SECTORS

4.2.3. Water balance

The water balance for existing conditions or baseline scenario in reference to water availability and demand in Mukungwa catchment was done following the water balance principle. The water demand is considered for the large sectoral water demands including domestic, irrigation, and industries. The outcomes indicate surplus water availability in Mukungwa catchment for existing or baseline conditions. It is also important to differentiate full water balance and manageable water balance.

4.2.3.1. Full Water Balance

The following are incoming & outgoing terms of full water balance to be analysed in the table11.

- **Precipitation**

It is the volume or depth of rainfall that fell in the catchment. It is the source of evapotranspiration, surface runoff and infiltration to groundwater. As the Mukungwa catchment is characterized by high rainfall, it generates around 2,246 Mm^3 annually.

- **Return flows**

Return flows are the fraction of the water used by Domestic, Industry, Mining and Irrigation, which is not consumed and flows back to the environment. The assumptions used in the Sebeya Catchment Plan (MoE, Sebeya Catchment Management Plan (2018-2024), 2018) were adopted in this study. The total return flows from all demand sites in the catchment, were found to be 29 Mm^3 annually.

- **Storage change**

Storage change refers to an increase or decrease in soil moisture over the period of interest. If you set up the water balance of a month with relatively little rainfall for example, a significant amount of water that the vegetation uses will come from the water stored in the soil. Therefore, during this month, soil water can be a significant source of water. However, during a wet month, the soil water storage will actually increase, and instead of being a source of water, the soil during this month functions as a sink. The storage change within the Mukungwa catchment is around 17 Mm^3 annually.

- **Inflows**

Inflows in the water balance refers to water flowing into the catchment or area of interest from neighbouring areas or watersheds. Therefore, this can be a river that flows into the area, or an external water transfer. For this case, Mukungwa Catchment is the most upstream of the Nile basin without any river or any water transfer flowing into it.

- **Evapotranspiration (ET)**

Evapotranspiration is the sum of water evaporation and transpiration from a surface area to the atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and water bodies. The evapotranspiration as the major outflow in the catchment is around 1,047 Mm^3 annually.

- **Withdrawals**

The withdrawals concern all the water supplied to the water demand nodes. In this study, this includes domestic, industrial, irrigation and Mining. The total water withdrawals in Mukungwa catchment is not high, as it was found to be 48 Mm^3 for the baseline situation of 2020.

- **Outflow**

Outflow refers to all water flowing out of the catchment, generally to downstream areas (river) or possibly by a water transfer outside of the catchment. As the Mukungwa catchment is considered as water tower (RNRA, 2015), the annual outflow is much higher than abstractions, and was found to be 836 Mm^3.

- **Groundwater recharge**

Groundwater recharge is the water that percolates through the soil and replenishes the aquifers. Some of this becomes base-flow, another part may flow through groundwater flow across the watershed boundaries to other areas outside of the watershed. A hydrogeological study and model can provide insight in these flows. WEAP has only a very simple representation of groundwater bodies. Still, it provides an approximation of the relevance of groundwater recharge on the water balance. The geology of the Mukungwa catchment allows high groundwater recharge with around 363 Mm^3 annually.

TABLE 11: SUMMARIZED FULL WATER BALANCE FOR THE ENTIRE MUKUNGWA CATCHMENT FOR THE BASELINE (2020).

IN (Mm^3)		OUT (Mm^3)	
Precipitation	2,246	Evapotranspiration	1,047
Return flows	29	Withdrawals	48
Storage change	17	Outflow	836
Inflow	-	Groundwater recharge	363
Total	2,293	Total	2,293

4.2.3.2. Manageable Water Balance

Here below are other incoming terms of manageable water balance, which are analysed in the table 12.

- **Runoff**

Runoff is the flow of water occurring on the ground surface when excess rainwater, can no longer sufficiently rapidly infiltrate in the soil. This can occur when the soil is saturated by water to its full capacity, and that the rain arrives more quickly than the soil can absorb it. Surface runoff often occurs because impervious areas (such as roofs and pavement) do not allow water to soak into the ground. The high rainfall and steep slopes of the catchment, allows much surface runoff, which was found to be around 60.3 Mm^3 annually.

- **Baseflow**

Baseflow is a portion of streamflow that is not directly generated from the excess rainfall during a storm event. In other words, this is the flow that would exist in the stream without the contribution of direct runoff from the rainfall. It is water seeping into the stream from groundwater, and helps keep water in streams during droughts. In WEAP model, baseflow corresponds to what is called “Interflow”: meaning that water infiltrating in the soil and slowly released through the sub-surface. The geology of the Mukungwa catchment with larva characteristics, allows much baseflows to respond in the river system with around 620.8 Mm^3 annually.

- **Groundwater**

When rain falls to the ground, some water flows along the land to streams or lakes, some water evaporates into the atmosphere, some is taken up by plants, and some seeps into the ground. As water seeps into the ground, it enters a zone referred to as the unsaturated zone. Water moves through the unsaturated zone into the saturated zone, where the interconnected openings between rock particles are filled with water. Groundwater is the water found underground in the cracks and spaces in soil, sand and rock. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers. The investigation of groundwater characteristics may require high technology and much logistics, but using WEAP model, the Mukungwa catchment groundwater was estimated at 173 Mm^3 per year.

TABLE 12: SUMMARIZED MANAGEABLE WATER BALANCE FOR THE ENTIRE MUKUNGWA CATCHMENT FOR THE BASELINE (2020).

IN (Mm^3)		OUT (Mm^3)	
Runoff	60.3	Domestic	31.7
Baseflow	620.8	Industries	0.1
Groundwater	173.0	Irrigation	10.4
Return flows	29.3	Mining	5.7
		Outflow	835.5
Total	883.4	Total	883.4

4.3. Water demands and water allocation under developed scenarios in 2030 and in 2050

In this section, the results for the projections and scenarios are presented with the focus on 2030 and 2050, which represent the sectoral water demand as well as environmental flow requirement (EFR). The analysis for water availability and water demand for different scenarios was conducted for supporting proper planning and decision-making.

4.3.1. Water Demand

The projected water demands are mainly influenced by population growth and socio-economic development in the catchment including irrigation sector. In comparing scenarios, the water demand increases more over time under all scenarios. The projected water demands for all sectoral users under 2030 and 2050 are presented in the table 13 and table 14 respectively. In 2030 projection for all scenarios, the annual water demands is expected to be 346.3Mm^3, while in 2050, water demands are expected to be 366.8Mm^3 as shown in the figure 24 and figure 25 respectively.

TABLE 13: PROJECTED 2030 WATER DEMAND FOR ALL SECTORS IN (TCM OR 1000M3)

	Domestic	Industries	Irrigation	Mining	EFR	Total water demand
Jan	3,999	8	653	544	18,280	**23,484**
Feb	3,638	8	-	495	19,043	**23,184**
Mar	3,999	8	-	544	23,503	**28,054**
Apr	3,870	8	-	527	27,799	**32,204**
May	3,999	8	1,306	544	31,337	**37,195**
Jun	3,870	8	2,612	527	22,745	**29,761**
Jul	3,999	8	3,265	544	20,892	**28,708**
Aug	3,999	8	2,612	544	20,892	**28,055**
Sep	3,870	8	1,306	527	20,218	**25,928**
Oct	3,999	8	-	544	23,503	**28,054**
Nov	3,870	8	653	527	25,272	**30,329**
Dec	3,999	8	653	544	26,114	**31,319**
Total	**47,106**	**100**	**13,059**	**6,413**	**279,597**	**346,275**

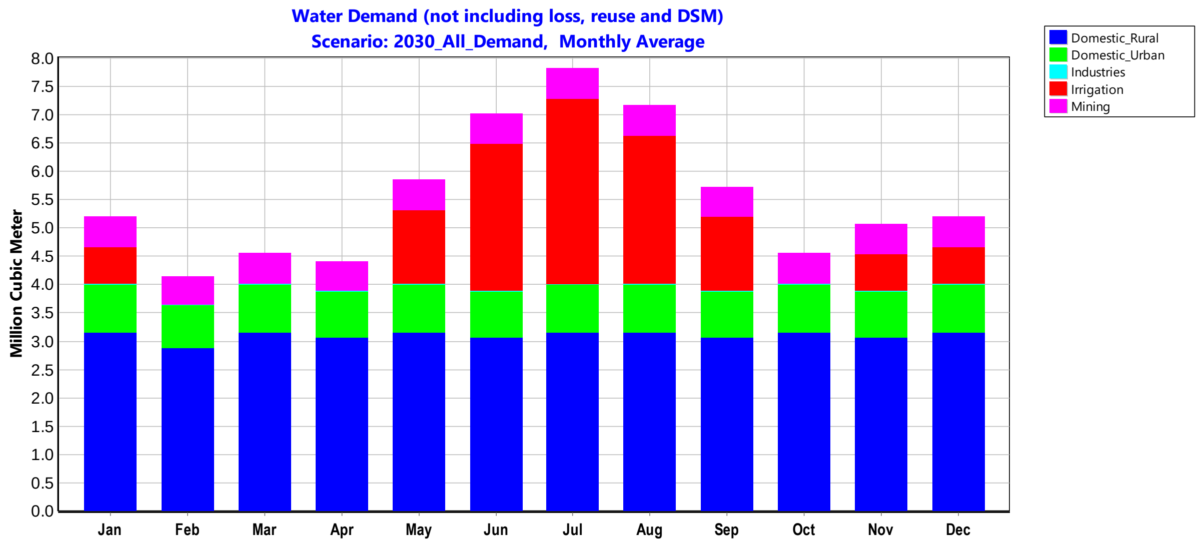

FIGURE 24: MONTHLY WATER DEMAND FOR 2030 PROJECTION EXCLUDING EFR.

TABLE 14: PROJECTED 2050 WATER DEMAND FOR ALL SECTORS IN (TCM OR 1000M3)

	Domestic	**Industries**	**Irrigation**	**Mining**	**EFR**	**Total water demand**
Jan	4,095	18	1,526	693	18,280	**24,613**
Feb	3,730	16	-	631	19,043	**23,420**
Mar	4,095	18	-	693	23,503	**28,309**
Apr	3,963	17	-	671	27,799	**32,450**
May	4,095	18	3,053	693	31,337	**39,196**
Jun	3,963	17	6,105	671	22,745	**33,501**
Jul	4,095	18	7,632	693	20,892	**33,330**
Aug	4,095	18	6,105	693	20,892	**31,803**
Sep	3,963	17	3,053	671	20,218	**27,922**
Oct	4,095	18	-	693	23,503	**28,309**
Nov	3,963	17	1,526	671	25,272	**31,450**
Dec	4,095	18	1,526	693	26,114	**32,447**
Total	**48,249**	**212**	**30,527**	**8,166**	**279,597**	**366,751**

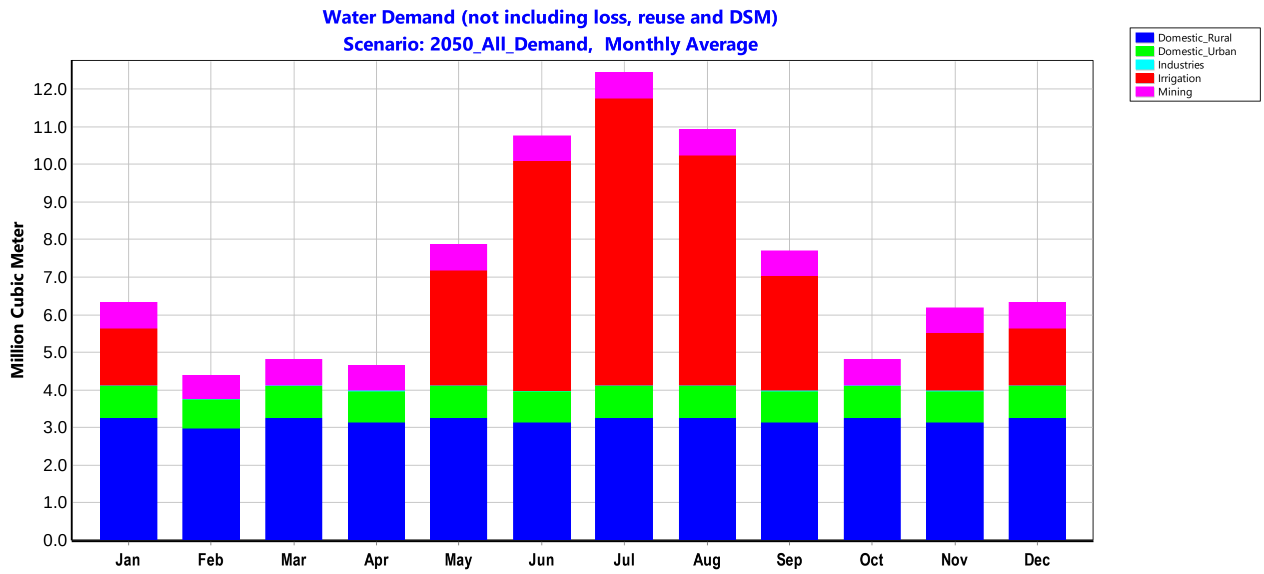

Figure 25: Monthly water demand for 2050 projection excluding EFR.

From the monthly water demand analysis, it shows that the peak water demand is expected to be in the month of July, mainly influenced by the expected irrigation development in the catchment. The trend of water demand from 2020 up to 2050 shows that water demand is expected to increase at almost double in 2050 as analysed in the figure 26.

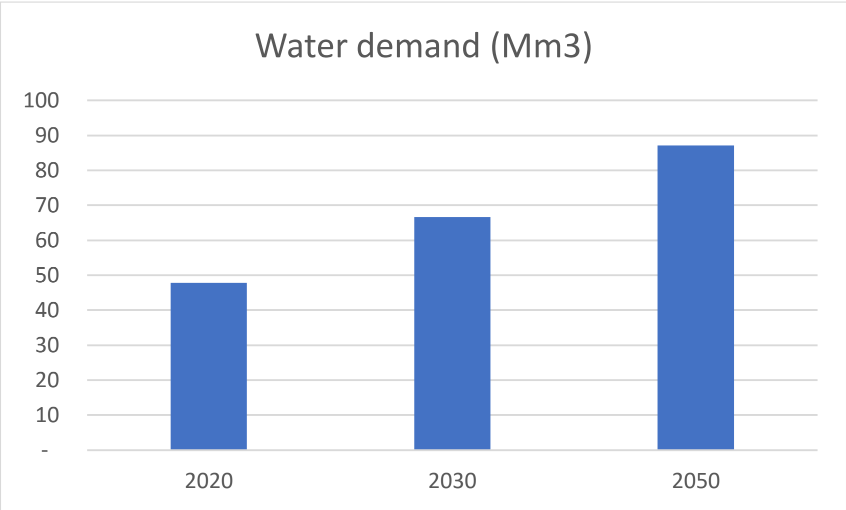

Figure 26: Water demand trend from 2020, 2030 to 2050 excluding EFR

4.3.2. Water Resources and Water Demands Analysis

The water resources availability and water demands relationships were analysed for the years of 2030 and 2050 to evaluate the water balance as detailed in the table 15. The relationships were analysed considering the three scenarios: increase in population growth, increase in economic development and implementation of environmental flow requirement.

TABLE 15: WATER AVAILABILITY AND WATER DEMAND FOR 2030 AND 2050 PROJECTION IN (TCM OR 1000M3)

	Water availability	Total water demand	
		2030	**2050**
Jan	64,971	23,484	24,613
Feb	69,653	23,184	23,420
Mar	77,508	28,054	28,309
Apr	87,591	32,204	32,450
May	82,516	37,195	39,196
Jun	71,429	29,761	33,501
Jul	61,020	28,708	33,330
Aug	56,537	28,055	31,803
Sep	58,722	25,928	27,922
Oct	62,901	28,054	28,309
Nov	71,542	30,329	31,450
Dec	71,128	31,319	32,447
Total	**835,518**	**346,275**	**366,750**

It is unfortunate that, during the months of June, July and August, the water availability or river flow reduces at its minimum level, while water demands increase at its peak level, because of increase in irrigation water requirement in dry season. This highlights the need of artificial water storage for balancing water availability and demand across seasons.

It is important to highlight that Mukungwa catchment has enough water to meet its demand in all consumptive sectors including environmental flow requirement up to 2050 without any water deficit a cross the months. However, hydropower water demand will experience high reduction in its production during dry season, as all existing hydropower plants are designed in the option of maximising the available flow in the river system.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

Mukungwa Catchment is water tower in Rwanda, providing source of water for different water use sectors such as hydropower, domestic, irrigation and industries, not only for the Mukungwa catchment itself, but also for countrywide and downstream countries of the Nile Basin. Analysing its water balance using WEAP model helps decision makers in future managing the natural variability of water availability, and frequent or unexpected water shortfalls. The future water demands have been assessed under given scenarios: an increase in population growth, an increase in economic development, and implementation of environmental flow requirement. A rising population and increasing water demands in urban and rural areas in conjunction with increased irrigation and industries activities and the implementation of an environmental flow requirement will greatly intensify the need for careful water resource management. The reference period in the assessment of the impacts of increased water demands in the Mukungwa catchment is 2020. The assessment of projected water demand was done for the years of 2030 and 2050 as detailed in the previous sections.

The aim of this study was to assess the current and future water resources availability & demands and developing water allocation plan for Mukungwa catchment using WEAP model as a Decision Support System (DSS),

- The characterization of Mukungwa Catchment was done based on the consultations with various institutions, GIS based data analysis and processing, as well as useful literature.
- The Mukungwa WEAP model developed is a state-of-the-art using the most recent data available.
- The WEAP model was calibrated and validated using the ground stations observed data.
- The proposal for current water allocation for the various water uses in the Mukungwa catchment (such as domestic, industrial, irrigation and environmental demands, etc.) was developed.
- The analysis of stream flow shows that the flow becomes minimal in July, August and September, and is at its maximum in March, April, May and November.
- The WEAP Modelling results on water availability confirm the statement of the National Water Resources Master Plan, saying that "*Mukungwa catchment is water tower of Rwanda*".
- Population growth, the expansion of irrigation activities and EFR put pressure on the water resources of the Mukungwa catchment and the model results show that the water demands are expected to almost double in the year of 2050.
- However, the WEAP modelling results indicate that there is no unmet demands in the years up to 2050 for all water demand sectors, namely, domestic, irrigation, industry and EFR requirement.
- The modelling results show that current water availability is enough to satisfy the water demands under current conditions as well as projected water demands in all water consumptive sectors.
- The water balance of the Mukungwa catchment was analysed for both current situation and projected scenarios, for supporting decision making in water resources management.

5.2. Recommendations

This study provided useful information on projected water demands in different sectors and water resource allocation and planning in the Mukungwa catchment. It also indicates that exploiting river water alone would affect existing hydropower plants production especially in dry season. Hence, it is necessary to take into account groundwater reserves that are or could be exploited.

The key recommendations from the study are provided here below:

1. As the Mukungwa catchment is characterized by steep slopes and high rainfall; it is recommended to put in place flood control and mitigation measures, to avoid water related disasters.
2. The WEAP modelling exercise included some assumptions. When accurate data are available, the model should be updated accordingly.
3. A water allocation and balance analysis of the Mukungwa catchment was carefully conducted for the current conditions and the projections of 2030 and 2050; it is recommended that the results be used to assist in water resources decision making and planning.
4. Water allocation should be applied based on water resources availability, by carefully considering the location point of abstractions vis a vis the location of existing hydropower plant, to avoid potential conflict.
5. As streamflow reduces during dry season, while water demands increase at its peak level during the same period; the development of artificial water storages is recommended for balancing water availability and demand across seasons.
6. The WEAP Model provides a wide range of planning and management modelling options. This study provided results on projections (which are future scenarios that can be hardly influenced by water planners and/or decision makers); it is recommended for conducting additional modelling of alternatives (which are interventions, and/or adaptations, which can be initiated by policymakers and implemented by water managers that will optimize water resources management), for coping future challenges in water resources management;
7. The WEAP model developed is quite sophisticated and extensive. However, changes in projections and inclusion of alternatives can be entered reasonable easily as the model was developed to ensure easy updating.
8. A comprehensive research on environmental flow requirement including downstream catchments water demand is recommended.

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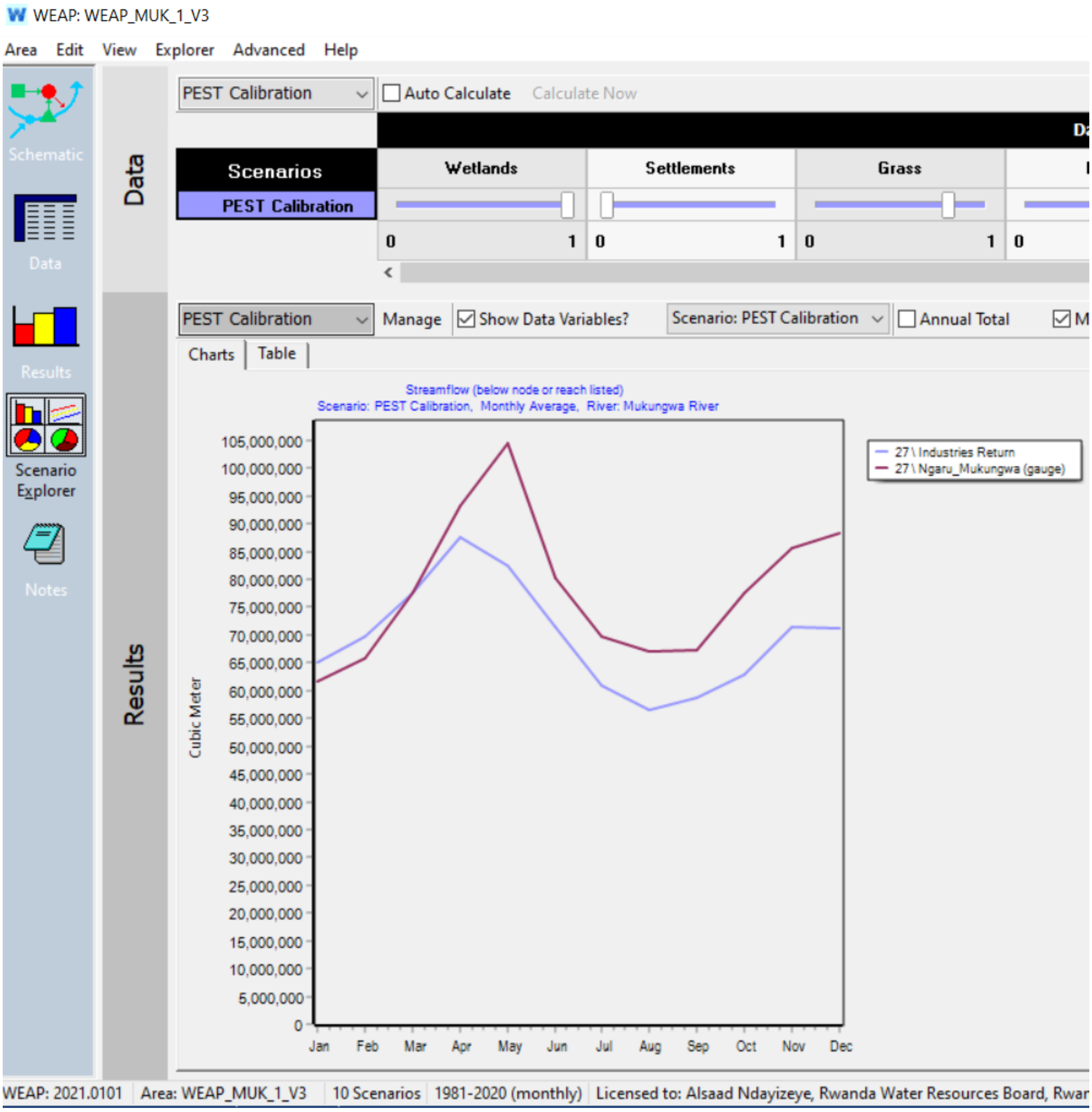
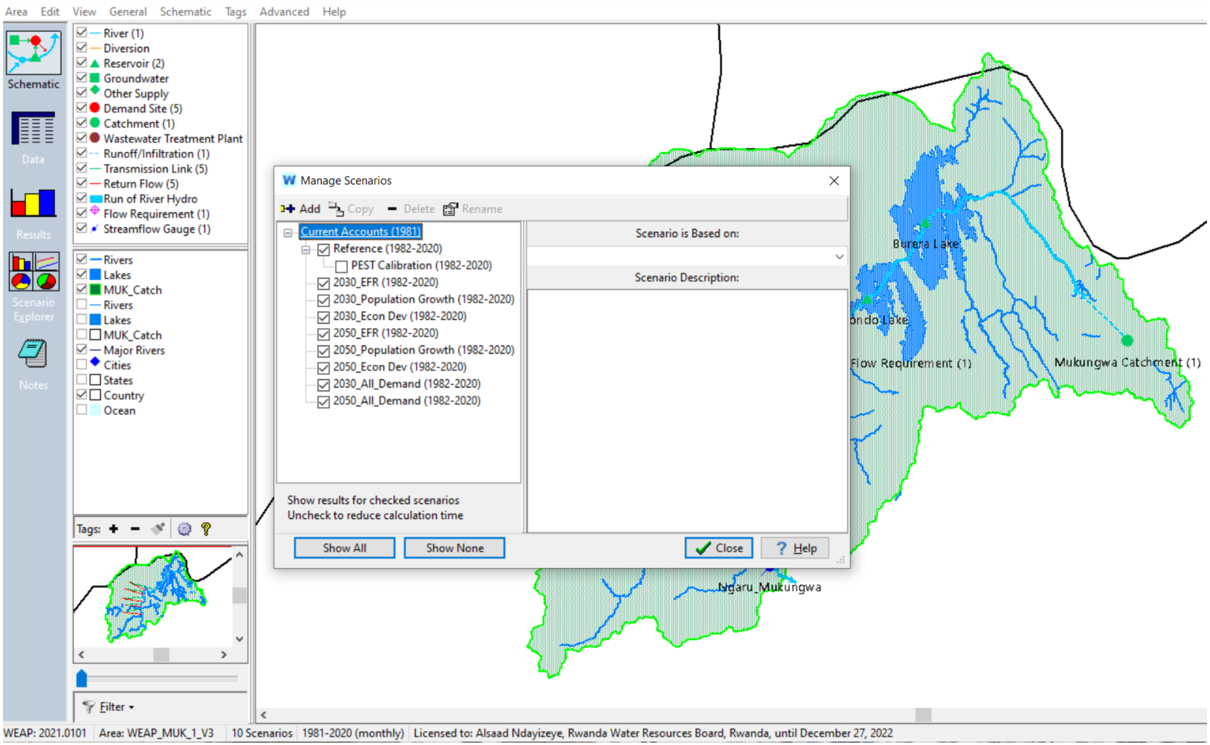
Appendix:

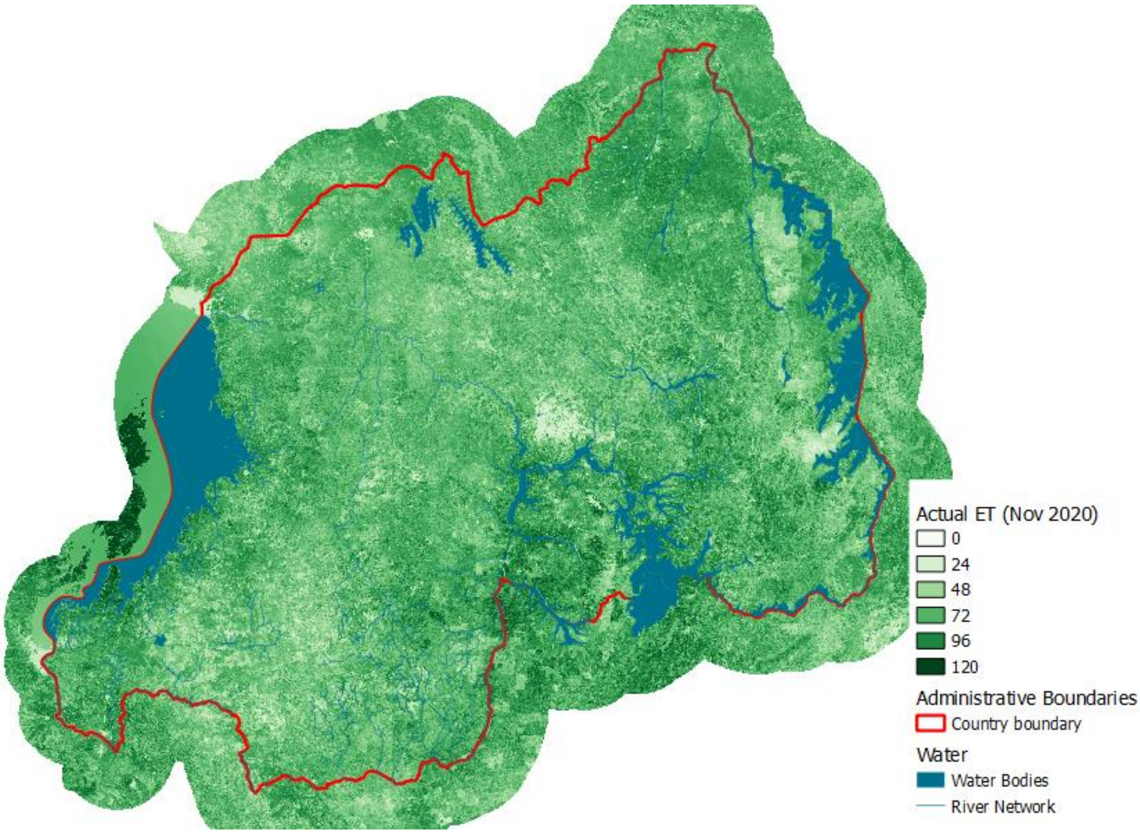
Appendix 1: PEST Calibration for WEAP Mukungwa.



Appendix 2: Scenarios development in WEAP Model.



Appendix 3: WaPOR data for the monthly ETa in Rwanda.



Appendix 4: Hydromet Station Network