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Title: ***Assessment of Needs and Options for Sustaining Ecological Water Supply to Ruaha National Park in Tanzania through Damming Ndembera in Iringa Tanzania***

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DECLARATION

I, Lusekelo Kibanda, the undersigned, declare that this thesis entitled "*Assessment of Needs and Options for sustaining ecological water supply to Ruaha National Park in Tanzania through damming Ndembera River in Iringa Tanzania*" is the result of my work and that it has not been presented to any other learning institution for a similar award of degree, diploma or other professional. Where other sources of information have been used, they have been acknowledged. I understand that non-adherence to the principle of academic honesty and integrity, misrepresentation/fabrication of any idea/data/fact/source/ will constitute sufficient ground for disciplinary action by the university.

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This Thesis has been submitted with my approval as a University Supervisor.

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DEDICATION

I dedicate this work to Almighty God, my family and all who have helped me all the way to this achievement.

ABSTRACT

Ndembera river is one of the rivers contributing to the Great Ruaha River (GRR) basin in Tanzania. Since 1993, GRR flow started to cease during the dry period due to over-abstraction of water from the river for upstream irrigation activities. Thus, it was essential to evaluate the water resources availability in the catchment and analyze options available to sustain the ecological water supply in the Ruaha National Park (RNP) and to satisfy other water users in the basin. The study used the Water Evaluation and Planning (WEAP) model as Decision Support System (DSS) to simulate current demand and forecast future water availability. This aimed at predicting the possible impacts on the water balance and allocation to various water demand sites. The study used historical data (1990-2018) to simulate water supply and demand in the GRR basin for the period 2019 to 2050. The calibration of the streamflow data for the period 1990 to 2005 was performed, and validation for the period 2006 to 2015 from two gauging stations. The scenarios involved in this study were: population growth of 2.2% and high population growth rate of 2.8%. Other scenarios were; expansion of irrigation farming area by 50% and 100% of the current area; improvement of irrigation systems and water abstraction infrastructures; construction of two dams in the Ndembera river; implementation of environmental flow requirement (EFR), and impoundment of the Ihefu Swamp. The study involved the evaluation of five water demand sites: namely, domestic, agriculture, livestock, bricks making, and EFR. The improvement of irrigation systems was found to reduce the irrigation water demands from 33.2MCM (2018) to 22MCM (2050). High population growth led to an increase in unmet demand from 2024 (580 to 600TCM) to 2050 (20 to 30TCM) under reference and high population scenarios respectively. The construction of Lugoda dam was found to increase irrigation water demand coverage from 80.87% to 98.17%. The introduction of (EFR) for (RNP) was found to compromise the water demand coverage for other sectors in the basin. Thus, the impoundment of Ihefu swamp showed to facilitate the 100% water demand coverage for all demand sites throughout a year. Also, data available regarding the availability of groundwater resource showed a maximum of 5L/s available for domestic tail-enders. Moreover, the study showed that Mwagusi, Itiku, and Mdonya rivers found within RNP are potential for impounding and hence being used for ecological water supply during the dry period. However, for effective management of the river flow, EFR consideration, control of illegal water abstraction, and timely granting of water rights are recommended.

RÉSUMÉ

La rivière Ndembera est l’un des cours d’eau contribuant au bassin de la Grande rivière Ruaha (GRR) en Tanzanie. Depuis 1993, le débit de GRR a commencé à cesser pendant la période sèche en raison du captage excessif de l'eau du fleuve pour les activités d'irrigation en amont. Il était donc essentiel d'évaluer la disponibilité des ressources en eau dans le bassin versant et d'analyser les options disponibles pour maintenir l'approvisionnement écologique en eau du parc national de Ruaha (PNR) et satisfaire les autres utilisateurs de l'eau du bassin. L'étude a utilisé le modèle d'évaluation et de planification de l'eau (WEAP) en tant que système d'aide à la décision (DSS) pour simuler la demande actuelle et prévoir la disponibilité future de l'eau. Cela visait à prévoir les impacts possibles sur le bilan hydrique et à les répartir entre divers sites de demande en eau. L'étude a utilisé des données historiques (1990-2018) pour simuler l'offre et la demande en eau dans le bassin du GRR pour la période allant de 2019 à 2050. L'étalonnage des données sur le débit de la période 1990 à 2005 a été effectué et la validation pour la période 2006-2015 à partir de deux stations de jaugeage. Les scénarios retenus dans cette étude étaient une croissance démographique de 2,2% et un taux de croissance élevé de la population de 2,8%. D'autres scénarios étaient l’extension de la superficie des cultures irriguées de 50% et 100% de la superficie actuelle; amélioration des systèmes d'irrigation et des infrastructures de captage d'eau; construction de deux barrages dans la rivière Ndembera; mise en œuvre des exigences en matière de débit environnemental et mise en fourrière du marais Ihefu. L'étude comprenait l'évaluation de cinq sites de demande en eau à savoir: domestique, agriculture, élevage, fabrication de briques et EFR. Il a été constaté que l’amélioration des systèmes d’irrigation réduisait la demande en eau d’irrigation de 33,2 millions de m3 (2018) à 22 millions de m3 (2050). La forte croissance démographique a entraîné une augmentation de la demande non satisfaite de 2024 (580 à 600TCM) à 2050 (20 à 30TCM) selon les scénarios de référence et les scénarios de forte population. Il a été constaté que la construction du barrage de Lugoda augmentait la couverture de la demande en eau d'irrigation de 80,87% à 98,17%. L’introduction de (EFR) pour (RNP) a été jugée compromettre la couverture de la demande en eau pour d’autres secteurs du bassin. Ainsi, la mise en eau du marais d’Ihefu a permis de faciliter la couverture de la demande en eau à 100% pour tous les sites de la demande tout au long de l’année. De plus, les données disponibles sur la disponibilité des ressources en eaux souterraines indiquaient un maximum de 5 L / s disponibles pour les utilisateurs domestiques. En outre, l'étude a montré que les rivières Mwagusi, Itiku et Mdonya présentées dans le RNP sont susceptibles d'être retenues et sont donc utilisées pour l'approvisionnement écologique en eau pendant la période sèche. Toutefois, pour une gestion efficace du débit de la rivière, il est recommandé de prendre en compte le RFE, de contrôler les prélèvements illégaux d’eau et d’octroyer rapidement les droits d’eau.

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LIST OF ABBREVIATIONS

ABF	Average Base Flow
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information Systems
BAT	Best Available Technology
BBM	Building Block Method
CC	Climate Change
CUMECS	Cubic Meter per Second
DANIDA	Danish International Development Agency
DEM	Digital Elevation Model
DRIFT	Downstream Response to Imposed Flow Transformations
DSS	Decision Support System
EFA	Environmental Flow Assessment
EFR	Environmental Flow Requirement
ELOHA	Ecological Limits of Hydrologic Alteration
EPAM	Expert Panel Assessment Method
FDC	Flow Duration Curve
GoT	Government of Tanzania
GRR	Great Ruaha River
GWP	Global Water Partnership
HEP	Hydro Electric Power

IFRM	Instream Flow Incremental Methodology
IM/L	Improved Mechanized Schemes Cultivated on Large Scale
IT/S	Improved Traditional Scheme
IWR	Irrigation Water Requirement
IWRM	Integrated Water Resources Management
MAE	Mean Absolute Error
MAF	Mean Annual Flow
MCM	Million Cubic Meter
MGRR	Middle Great Ruaha River
MoW	Ministry of Water
NAWAPO	National Water Policy
NBS	National Bureau of Statistics
NRB	Niger River Basin
PEST	Parameter Estimation
PET	Potential Evapotranspiration
PHABSIM	Physical Habitat Simulation System
RBWO	Rufiji Water Basin Offices
RC	Regional Cooperation
REALM	Resource Allocation Model
RMSE	Root Mean Square Error

RNP	Ruaha National Park
RSA	Republic Of South Africa
RVA	Range Variability Method
SDG	Sustainable Development Goals
SEI	Stockholm Environmental Institute
SMUWC	Sustainable Management of Usangu Wetland and Catchment
SWAT	Soil Water Analysis Tool
TCM	Thousand Cubic Meters
TWSDP	Tanzania Water Sector Development Program
US	United State
WEAP	Water Evaluation And Planning
WRM	Water Resources Management
WRMA	Water Resources Management Act
WWF	World Wildlife Fund

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Globally, Freshwater resources availability and accessibility are under increasing threat from human activities (Tesfamariam, 2018b). These activities are both consumptive and non-consumptive use like domestic supply, industrial uses, hydropower generation, and irrigated agriculture. Additionally, to achieve these needs, different techniques like water diversion, inter-basin water transfer, water impoundment, and abstraction of river run-off have been employed (Richter et al., 2011). These activities have then led to significant alteration of rivers flow in the Great Ruaha River in Tanzania and the world at large.

To respond to such river flow challenges, there is the growing consensus that the rivers are appropriate water users and as such minimum flow management, which encompass the release of water from the dams or reservoirs specifically for environmental or ecological flows so as to maintain, protect and restore the river ecosystems (Szemis, 2014). These minimum flows often referred to as ecological or environmental flows which are then provided not only for ecosystem services but also to the increase of socioeconomic activities (Ormazabal, 2004). Although ecological and environmental flows terminologies are often used interchangeably, according to academic literature, there is a minor difference between them: The ecological flow is a minimum flow needed to preserve the existing river ecosystems. The minimum ecological flow is limited to low flows during dry seasons to sustain life in the river (Vélez et al., 2015).

The allocation of minimum flow for maintaining the ecological systems of the rivers, the flow regimes need to involve natural variability of the river flow (Bunn and Arthington, 2002) including other aspects related to the magnitude, frequency, duration, timing as well as rate of change of the river flow (Tonkin, Jähnig, & Haase, 2014).

However, Tanzania has recognized the importance of a healthy river and its functions to the environment and societies in boosting the socio-economic status hence alleviating the poverty, hunger, and health problems (Sirima, 2010). This can be justified due to the adoption of the principle of environmental flows in the Tanzania National Water Policy of 2002 (Mbungu &

Kashaigili, 2017), and then disseminating them more in the concept of "environmental reserve" in the Water Resources Management Act of 2009 (WRMA, 2009).

Among of the significant challenges in ensuring sustainable management of water resources is to know how much can be taken from the river without compromising its ability to meet ecological, social and economic needs (Kashaigili et al., 2005). The mechanism of water allocation and estimation of water required for the environmental reserve is another challenge especially for a closely regulated river like the Great Ruaha River (GRR), at the same time making sure that the lives of the poor who depend on the water are not affected.

The GRR is one of the major tributaries of the Rufiji River in Tanzania. It is the most important river in the Rufiji basin as it produces over 50% of hydroelectric power installed in the country (Jambiya, 2005). The river is also being used for irrigation which makes an essential contribution to the livelihood of rural people (Kihwele et al., 2018b). Additionally, the river supports the ecology of the Usangu wetlands, a valuable freshwater and a vital role of supporting the lives of the significant wildlife reserve in Ruaha National Park (RNP) found in Iringa Tanzania (B. A. Lankford, Tumbo, & Rajabu, 2009).

For about three decades, the GRR which flows through the RNP has ceased carrying water during the dry season. This cessation of flow has been prolonging to periods of zero flow (Thomas, Holbro, & Young, 2013). According to Jambiya (2005), the drying of the GRR has been caused by different anthropogenic activities conducted in the catchment area. These activities are like water-intensive abstraction for irrigation agriculture and domestic water use. Another cause is clogging of channels in the Ihefu swamp, which leads to ponding and increased loss of water through evapotranspiration (Kihwele et al., 2018a).

The drying up has caused adverse effects to the ecosystems of the RNP, including loss of many animals' lives and aquatic species (i.e. hippopotami, fish, and freshwater invertebrates) and hence triggering changes in their behaviors and sustainability (J. Kashaigili, Mccartney, & Mahoo, 2006). This has also resulted in social conflicts between the upstream users and downstream users as well as a reduction in hydropower generation in the Mtera and Kidatu dams downstream (Kihwele et al., 2018b).

Considering its importance for maintaining the biodiversity of the river and the long-term sustainability of the entire Ruaha National Park (RNP), this is likely to be dependent on the restoration of perennial flows in this, the only naturally occurring year-round river in the national park. From different studies conducted in the Rufiji river basin (Rufiji Basin Water Board, 2015), the Ndembera River was found to be one of the potential rivers for the construction of those dams for the generation of hydropower as well as having the water release for other uses downstream particularly the water demand supplies for RNP (Mtahiko et al., 2006).

However, these and other issues regarding the flows within the GRR led to the importance of assessing the needs and options for sustaining the ecological water supply through damming Ndembera river. This dam will enable the regulated flow to the GRR during the dry season. In this research, the hydrological modeling and WEAP models (WEAP software and ArcGIS) will be used to evaluate the water demand, analyze the river flow required from the dam to RNP, planning, and identification of a range of options for the water use planning and distribution.

1.2 STATEMENT OF THE PROBLEM

The Great Ruaha River basin is among Tanzania’s most significant river basins. The basin areas are generally used for rice production in Tanzania, and it embraces the Usangu plains and wetlands. The river is a primary source of water for RNP and its ecological systems. The river is also serving the water to two national hydroelectric power dams (Kidatu and Mtera) which provide over 50% of the national hydroelectric power. Moreover, the river is crucial for pastoralism, fishing, bricks making activities as well as domestic water supply.

According to the Rufiji Basin Water Board (2015), different animals and over 400 species have been affected by the seasonal drying of the GRR since the 1990s. The seasonal dry of the river flow has been attributed by an increase in the uncontrolled abstraction of water in the upper stream of the river. Also, the rise in water competition from farmers, pastoralists, fishers, and domestic water demand has been affecting the river flow especially downstream. This has consequently affected the ecological system of the RNP and Kidatu and Mtera hydroelectric power generation dams (Mwakalila, 2013). Accordingly, the socio-economic, cultural, and ecological consequences of the flow cessation of the river have been noticeable.

Through different studies conducted in the catchment, Ndembera River is the only river which flows throughout the year and has a high potential for production of hydroelectric power through damming in the upper stream of the river (Mtahiko et al., 2006).

Thus, different researches examined the causes of drying of the river, effects attributed to the seasonal dry of the river, the potentiality of the Ndembera River for hydropower generation and supplying water to downstream existing dams used for the production of hydropower and best ways on managing agricultural activities taking place upstream of the river.

So far, there is an inadequate assessment of the needs and options for restoring the river flow, which affects water availability for RNP in Iringa, Tanzania. For this reason, the researcher was interested in conducting a study to examine the needs and options for sustaining ecological water supply to RNP through damming the Ndembera River.

1.3 RELEVANCE OF THE STUDY

The study is significant due to its endeavor to identify the needs and options in which seasonal drying of the GRR can be mitigated before the disappearance of the species which have been affected by the shortage of water during the dry season. The findings of this study were expected to provide insightful information for identifying potential demands stressing water utilization in Tanzania and the world as a whole.

The study has also proposed the options to be adopted to ensure the ecological system of the RNP is restored to its close approximately original environment. The study was expected to come up with suggestions on the policies to be adopted for the sustainable management of the river basin, environmental and ecosystems which depends on the river for their sustenance. Moreover, this study will not only be a useful reference for future studies but also will significantly boost the development of research on the environmental and ecological water management in the country and Africa as well as promoting the achievement of sustainable development goals (SDG 1, 2, 6, 7, 13, 14, and 15).

1.4 OBJECTIVE OF THE STUDY

1.4.1 Main objective

The main objective of this study was to assess the needs and develop different options for sustaining ecological water supply in the RNP through damming the Ndembera River.

1.4.2 Specific objectives

- To assess water demands for the ecological sustenance of RNP.
- To analyze the challenges and corresponding implications associated with water requirements for ecological sustenance of the RNP.
- To quantify and characterize the implications of other water demands that compete with the water requirements for ecological sustenance of the RNP.
- To critically review efforts expended previously to enhance water supply for ecological sustenance of RNP.
- To analyze engineering and other options suitable for addressing the challenges currently associated with water requirements for ecological sustenance of the RNP

1.5 RESEARCH QUESTIONS

1 What are the current and future water demands required for sustaining the ecological water supply for Ruaha national park?

2 What are the water demands and implications of other water users that compete with the water requirements for ecological sustenance of the RNP?

3 What are the effects imposed by the seasonal dry up of the Great Ruaha River in regards to the RNP and its riverine ecosystem?

4 What are the contributions and efforts expended by other researchers in addressing the challenge of water demand for ecological systems in RNP?

5 What are the potential options available for addressing the challenges of water supply to the RNP for sustaining the ecological systems?

1.6 THEORETICAL CONCERNS / SITUATING THE STUDY IN THE FIELD

The increase in agricultural land use, evapotranspiration in the wetlands and population growth in the Great Ruaha catchment area in Tanzania has led to the reduction of the magnitude of surface runoff, total water yields, and groundwater flow. Ndembera River is sole river found in the Great Ruaha River catchment area in which water flows throughout the year. This river has the potential for generating hydroelectric power, water supply, and environmental flow for the RNP through damming.

In other studies, the focus has been put on hydro-electrical power generation and irrigation farming in which the abstraction of the water for the irrigation and evapotranspiration has been affecting all hydrological cycle of the river catchment. Also, cessation of the river flow has been changing the water-related ecosystem found downstream such as ecology, irrigation, municipal water supply, and hydroelectric power generation.

However, this study focused on addressing the water demands for the ecology found in the RNP as well as other sectors competing in water demand with RNP. Through this study, different options for sustaining the water supply for the ecology were explored to facilitate the sustainable management of the environment, reduce hunger, and preserve the ecosystem.

1.7 SCOPE OF THE STUDY

This research covers the assessment of needs and options for sustaining ecological water supply to Ruaha National Park through damming Ndembera river in Iringa, Tanzania. The study involved simulation of streamflow data and climate data.

To achieve this objective, the study will involve combined approaches of literature review, data collection and analysis, and modeling. The vector file for the GRR and Ndembera river was developed by ArcGIS. These vector files were then imported into WEAP system for catchment delineation and scenarios analysis. The research does not cover studies on water quality and sediment analysis due to the shortage of time (four months) and financial limitations.

1.8 TENTATIVE THESIS CHAPTER OUTLINE

The first chapter of this study will involve the general introduction of the research topic. Following this introduction, the second chapter will present the literature review starting with the global perspective and environmental flow protection and the approaches to achieve a sustainable ecological water supply system. This section will also include a presentation of the theoretical background in the context of the pros and cons of various types of hydrological models and a thorough description of the general background of the study area.

In the third chapter, the existing situation of the study area concerning the ecological water supply for sustaining RNP. It is in this chapter where an overview of the current condition of the study area will be explored to give a better understanding of the real situation occurring to the ground. Moreover, this section will briefly describe the materials and methods used to carry out the study and the detailed description of the modeling procedure. Then**,** the fourth chapter will describe the results and discussions of different analyses and models applications. Finally, the firth chapter will be the conclusions and recommendations found from the study concerning the overall problems and approaches.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Water resources management

While water quantity and quality continue to worsen, water demand (competition) increases between development sectors (agriculture, human supply, industry, energy, ecosystem maintenance, etc.) and users (upstream and downstream). The management of freshwater resources has a central role in sustaining the human life; it is of critical importance to healthy social, economic and political wellbeing of the society, nation and the global as a whole (Schleiss & Matos, 2017).

The changing of water consumption patterns, pollution, and lack of environmental control attributed to the rapid population growth leads to global pressure on water demands. Sectoral approaches to water resources management have dominated in the past and are still prevailing. This leads to fragmented and uncoordinated development and management of the resource.

Generally, water management is fragmented among various users, institutions, and physical aggregation levels, with little regard for solving conflicts and competition (Kihwele et al., 2018b).

Different countries around the world formulate water laws and policies based on the principle of fair, equitable, and reasonable usage of water (TWSDP, 2012). The management of water resources catchment areas, sources, and infrastructures is the fundamental aim of the formulation of water policies (Ayele, 2016). In order to meet the present and future water demand and preventing potential water scarcity, crisis, conflicts and adverse effects to ecosystem, proper planning, evaluation, development, and allocation of water resources are essential (Desta & Lemma, 2017).

2.1.1 Sustainable Water Resources Management

Sustainable water resources management is described as managing water resources to safeguard the full enjoyment of the benefits associated with water and its ecosystem. The decrease in water quality and quantity have been influencing the conflicts between the water users. Sustainable water resources management focuses on designing and implementing a management program that will store and divert water for human activities without compromising the environment. This requires appropriate consideration of human water use, water availability, and the influence of human land use in the river basin. By doing so, human needs for water are met while maintaining the functions of the ecosystems and sustaining the services provided by the ecosystem (Tesfamariam, 2018).

The aim of studying environmental flow is to predict the ecological effects of the streamflow triggered by changes in water abstraction, water impoundments and improvement of irrigation techniques. Considering those scenarios, the need of prioritizing in sustainable management water resources has been regarded as a focal point for meeting the growing demand and achieve a safe and sustainable environment for future and resolving the conflicts among water user competing for sectors. The evaluation of the water demand for ecological sustenance becomes the basis for the environmental flow studies (Murphy et al., 2012).

2.1.2 Integrated Water Resources Management (IWRM)

According to Global Water Partnership, Integrated Water Resource Management (IWRM) can be defined as "*process that 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, p.10).

This concept of IWRM was adopted in the Dublin principles with its main three strategic objectives. These objectives are economic efficiency in water use, equity, environment, and ecological sustainability. Moreover, the implementation of IWRM depends entirely on three pillars (Jain & Kumar, 2014). These pillars are enabling environment (policies, legal framework, financing, and incentive structures), management instruments, and institutional roles (i.e. central, river basins, capacity building).

2.1.3 Riverine ecosystem

River system can be regarded as an independent ecosystem, which includes river channels, lakes, and land near the river or water bodies. The water quantity, quality, and aquatic species are the significant components of river ecosystems. The river ecosystem can be defined as part of the ecosystem, which is being affected by the change in the river flow regime. There are three main river functions (Li-juan & Hong-xing, 2008). These are ecological functions, environmental functions, and resource property.

The advantages of the river ecosystems can be as water for human needs, goods and other than water such as food, medicinal plants, recreation and energy (Vélez et al., 2015; Wahono, Legono, & Yulistiyanto, 2014). Other services provided by water flow are flushing of the sediments in the river, navigation, solute transfer, pollutants dilutions, groundwater recharge, and climate adjustment. Flooding plays a vital role in the ecology of riparian and floodplain plant communities and water drains off the land occupied by these communities soon after the recession of floodwaters (Okello, 2016). Thus, although IWRM is facing an essential challenge of balancing the water allocation between different uses, ecological sustainability, and economic efficiency remain central criteria for its implementation (Korsgaard et al., 2005). This can be emphasized by the fact that the conservation of riverine ecosystems by providing Water for Nature and internalizing the market and non-market values of goods and services sustained by such ecosystem are vital parts of IWRM.

The dynamic ecological balance is a fundamental criterion for the sustainable development of human civilization (Yan et al., 2012). For sustainable development to be achieved, it is crucial to harmonize between economic, environmental, and ecological aspects of the river system. Therefore, the water requirement for environment and ecology must be well considered a part of the water requirement beforehand and during the process of integrated planning of the river systems (Tesfamariam, 2018).

2.2 Water policies and water laws

Before the 1990s, the water supply planning and management in Tanzania was based on the administrative regions and was mainly focused on the provision of urban and rural water supply while irrigation and energy were carried out at the national level (Hirji & Davis, 2009). After this period, the achievement of the water demand to different sectors was not met. This led to conflict eruption between water users like the irrigation sector, pastoralists, and domestic water users. For the sake of resolving the conflicts over water demands, the review of the water sector was established in 1993 – 1994 (Lankford & Mwaruvanda, 2005). This review emphasized on the four key areas: full involvement of beneficiaries, the participation of private sectors, strengthening the legal and institutional framework, and management of necessary water resources.

In the mid of 1994, the government of Tanzania (GoT) in collaboration with DANIDA and the World Bank revealed that there was no intersectoral coordination between water use and management. This led to growing conflicts between different uses of water, limited stakeholder participation in decision making, inadequate incentives for efficient water use, and limited hydrologic and water use data on which rational allocation decisions could be based in the most river and lake basins (Hirji & Davis, 2009)**.**

As an initiative of tackling these conflicts, the National Water Policy has been reformed in 2002 (NAWAPO, 2002). The policy emphasized the provision of environmental flows due to its economic, livelihood and biodiversity values. To achieve this, the government announced all the water-dependent ecosystem areas as protected areas, national parks and game reserves (Koppen et al., 2016)**.** Such areas with water-dependent ecosystems are Serengeti, Ruaha, Lake Manyara, and Sadani National Parks, and the Selous Game Reserve (NAWAPO, 2002). This was followed by the establishment of a river or lake basin water offices. Moreover, the NAWAPO (2002) and the 2009 Water Resources Management Act:

- Recognized the importance of ensuring that ecosystem services are maintained through environmental water provisions
- Assigned the environment second priority for water allocation following basic human needs
- Recognized that best available scientific information should be applied to establishing environmental water requirements

The assessment of ecological and environmental flow requirement is highly supported by Tanzania's policies and legal frameworks. Such regulations and policies are; Tanzania National Water Policy of 2002, the Environmental Management Act of 2004 and Water Resources Management Act of 2009, National Land Policy of 1995, Wildlife Policy and Wetland Policy of 2007, National Agriculture Policy of 1997 and the National Livestock Policy of 1997and ultimately achievement of water, energy, food and ecosystem nexus goals.

2.2.1 Water Allocation Guidelines and Principles

Water allocation can be defined as the rules, and procedures used for deciding the water access or distribution for individual or collective use, in relation to water availability. In other words, water allocation is defined as a combination of actions that enable water users and water uses to take or receive water for beneficial purposes according to a recognized system of rights and priorities.

Water resources have been emerged to be one of the resources most impacted by human activities in the world. According to Kashaigili et al. (2005), it has been found that there is a gradual change of water allocations from being focusing on human needs only to water for the environment as among of the component of intersectoral water allocating processes.

The demand for achieving the equitable, efficient and sustainable use of water resources to meet the water demand for different sectors is increasing, especially in areas where water availability is diminishing (Kadigi et al., 2008). The changes in river flow have been an effect of water allocations amongst different sectors depending on the consumptive uses, which in turn leads to change in the flow regime of the river. These changes of the river flow have significant impacts on the ecological systems of the river. The recognition of the flow regime of the river for environmental management has been gaining the priority globally nowadays through promotion and implementation of SDG No 1, 2, 6, and 14. The application of integrated water resources management strategies encourages the consideration of environmental requirements during water allocations planning (Lankford and Mwaruvanda, 2005; Arthington et al., 2003).

In order to allocate the water required for the environment, there is a need to have a detailed understanding of the amount needed for ecological sustenance in the river basin. The balance between the water demands (environmental water demands and other competing water users) and available water is always a challenge arising during the planning of sustainable water distributions.

From different studies conducted in river basins in Tanzania, it has been found that water allocations are conducted in a priority-based system with national development policies and objectives (Franks, Lankford, & Mdemu, 2004). This approach is practically feasible for the basins with competing for water demands with limited availability of water supply such as the Rufiji river basin and Pangani river basin (King & Brown, 2006).

In Tanzania, the National Water Policy of 2002 and National Environmental Policy of 1997 recognizes the role of health river basin plays in providing domestic water, hydroelectric power, water supply for ecological maintenance as well as other economic benefits. The achievement of sustainable water management and secured society depends on institutions and approaches for water allocation reformed, especially for regions or basins having water resources shortages (Dinar, Rosegrant, & Meinzen-Dick, 1997).

Tanzanian national water and environmental policies emphasize that measures should be instituted to protect the wildlife and promotes sustainable wetlands management and use. For this reason, this thesis tries to uncover the needs and options for sustaining ecological water supply to RNP.

In order to come up with a sustainable and optimal decision in water resources allocations, different criteria have been used to compare forms of water allocation. These criteria are: (i) Flexibility in the distribution of supplies; (ii) Real opportunity cost of providing the resource is paid by the users; (iii) Political and public acceptability (iv) Predictability of the outcome of the allocation process; (v) Security of tenure for established users; (vi) Equity of the allocation process (Okungu, 2018).

The argument points out that the performance of such an allocation method could be evaluated by simulating the allocation process and estimating the social, economic and environmental effects of the resulting allocation schedules (Teka**,** 2014). Based upon the idea that the achievement of equitable and efficient water allocation requires all stakeholders' cooperation in sharing water resources, a modeling framework was proposed for obtaining equitable, efficient and sustainable short-term water allocations among competing water users and stakeholders in a river basin.

2.3 Ecological flow and Environmental flow assessment

The idea of the minimum flow of the river has become into practice since the 1970s following several studies which enumerated the understanding of the flow regimes of the rivers.

The flow regime is among the factors influencing the ecological systems of the river (Vélez et al., 2015). The complexity of the water uses, such as domestic water demand, agricultural supply, industrial supply, and hydropower generation, has created difficulties in estimating ecological and environmental flow (Jain, 2012).

Environmental flow is the water that is left in a river system or released into the river for the specific purpose of maintaining or managing the condition of the ecosystem depending on the particular stream. While the environmental flow is supporting the minimum flow, which is required not only for ecosystems but also for the development of economic activities, ecological flow ensures the conservation of the river basin ecosystems (Vélez et al., 2007). The environmental flow can be used to support the fishing, farming, drinking water supply, grazing land, pollution control, navigation, and protection of endangered species as well as cultural and spiritual values (Dickens, 2011). Considerable effort has been devoted to integrating the ecosystems into water resources management due to its vital contribution to the escalation of economic, social, cultural, and environmental benefits (Kihwele et al., 2018). The integration of ecosystems into water resources management led to the establishment of ecological flow management, which advocates the concept of Water-for-Nature (Korsgaard et al**.**, 2005).

Flow regimes

River flow comprises of water quantity, timing, and frequency of occurrence of flows. These flows depend entirely on the catchment attributes that are physiographic, underlying geology, vegetation cover, and the rainfall amount, intensity, timing, and frequency. The flow regime can be categorized into simplified flow components. These components which are examined in terms of timing, seasonality, frequency, and duration, are as follows:

a. Cease to flow: The cease to flow is the period of no observable flow in a river at a certain season particularly in the summer season which can lead to total or partial drying of the river channel (Tuan, 2010). Cessation of flow can be influenced by climate change or anthropogenic activities conducted within a catchment area. The cease to flow can result in periodic stress for the ecosystem and subsequently harmful effects if the cessation periods prolongs.

b. Low flow: This is a continuous flow of water into the river in a minimum amount. The flow may be limited by the narrow area of the channel but will provide flow connectivity between the habitats in the channel. This flow helps to support the life of the species as it acts as a refuge from high flows (Kumar et al., 2007).

c. Flash flood: Flash is small with short duration peak flow events. These are flows that exceed the base flows and last for several days, often as a result of intensive and sometimes localized rainfall. This flow is essential in improving the water quality and allowing the inputs of freshwater (Tuan, 2010).

These flow regimes play an essential role in regulating the ecological and biodiversity processes in the rivers (Ma et al., 2018)**.** This has been used to understand the flow variability of the river, evaluating the effect of streamflow on living communities and ecological processes, planning the conservation efforts for freshwater ecosystems as well as influencing the inventory of hydrologic types of water resources management (Sokile, Koppen and Lankford, 1993).

The achievement of the flow regime characteristics is mainly influenced by hydrologic indices with streamflow components such as magnitude frequency, duration, timing and rate of change of the flow. Also, the components of the natural flow of the river can be characterized by various time series and probability analyses such as high, low, or average flow.

2.4 Implications of other water demand that competes with the water requirements for ecological sustenance of the RNP

The GRR basin is a complex basin with various multi-sectoral water uses and users. The livelihood of the high population found in the catchment is mainly depending on irrigation and water-related activities such as livestock keeping, fishing, bricks making. More than a million small scale farmers located in the GRR basin produce a significant portion of the country’s food. Paddy irrigation is the main activity practiced in the basin and largest water user, particularly during the dry season (Sokile, Koppen, & Lankford, 2003). These large and small irrigation projects are mainly found in the upper course of the river.

During the wet season, the river flow is sufficiently used for different activities such as water abstraction for irrigation, domestic water uses, pastoralism, fishing, ecological systems, and hydroelectric power in the downstream. Unlike to wet season, the dry season is a water scarcity period and associated with water conflicts and disputes over access to water (Baker, 2015). In this season, the farmers and villagers along the rivers in the mid of the catchment divert water to both irrigated and fallow fields and to the village for domestic uses as well as bricks making which is both for domestic and commercial purposes.

A significant reason for the seasonal drying of the river is large- and small-scale dry season crop irrigation. The legal channelization of the water for irrigation schemes has also catalyzed the illegal diversions of water and satellite farms surrounding the rice schemes. Other causes include dry season use of surface water to meet domestic needs, reduction in flow resulted by possible changes in Usangu / Ihefu swamp configuration. Ifushiro swamp is also accounted for the tremendous loss of water by natural processes which result in no flow through it during the dry season. Moreover, the replacement of the western wetland by irrigation fields led to high loss of water through evaporation, unlike the wetland which had been helping in holding the water and slowly drain through the outlet (WWF, 2005).

The scarcity of water in the basin has caused several impacts to the water users. The conflicts over water uses and users which often occurs during the dry season particularly from June to November where high water abstraction for paddy irrigation, livestock watering occurs, hence leading to the cessation of river flow. Also, unauthorized water abstraction, especially brick making industry during the dry season, are among the sources of water management challenges facing domestic users (Ngowi & Makfura, 2015).

Also, the reduction of water flow into Mtera and Kidatu hydropower generating dams for the last 14 years has been an important cause of conflict between irrigation and hydropower sectors in the basin. This has been caused by the fact that the irrigation which is practiced in the upstream of the river basins takes advantage of abundant water resource to the expense of downstream users particularly HEP production (Mdemu & Magayane, 2014). The drying of the river has been impacting the economic livelihoods of the people in the basin. This has been caused by diminishing availability of pasture, water resources for livestock, abandoning of cropped areas, and reducing of fish production.

Moreover, over 50% of the hydroelectric power generated in Tanzania is from Kidatu and Mtera. This electricity saves over five regions such as Morogoro, Iringa, Dodoma, Pwani, and Dar es Salaam. The shortage of water due to drying up of the GRR has been leading to power rationing in the country hence affecting the economy of the country and its peoples.

Exclusion of pastoralists from Usangu Great river for grazing and watering to conserve the wetlands and the river has also been affecting the pastoralism activities and resulting into conflicts between herders and farmers due to competition over land tenure, water access, and even animals being kept in the farmer's crops cases. The increase in conflicts between wildlife and human. This has been caused by animals' movement for the search for water and food in such a way that they invade the people's crops.

Villagers are suffering from water shortages as the rivers they once relied on now dry up. At the maximum of the dry season, women and children need to walk up to 10 km to find water. In Usangu plains, this has been found to affect villages like Ukwaheri and Madundasi. Heavy use of fertilizers, pesticides, and herbicides has led to unknown levels of these chemicals in downstream water sources (pollution from agricultural chemical run-off) (WWF, 2005).

2.5 Effects of seasonal dry of river flow to the sustenance of ecosystems of RNP

The segment of the GRR which flows through the national park has a diversity of large mammals, aquatic ecosystem and a flourishing and growing tourism industry which provides much needed foreign currency for the Tanzanian government. Because the GRR is the only reliable source of water in the park which, in natural, conditions flows continuously. The following facts are exemplifying the importance of river flow as the primary driver of conditions in the park:

- The range of low to high floods of the river is essential to maintain the moisture, seed dispersion/ germination, seedling establishment, and growth. The riparian and floodplain vegetation which are mostly depending on the flows and water level in the river is the vital habitat for large mammal populations during the dry season.
- The riparian vegetation found in the river banks helps in stabilizing the river banks, especially during floods. The vegetation helps in reducing the erosion of the riverbeds

hence protecting the characteristic channel forms and habitats, especially with excessive sedimentation of the channel.

- The occurrence of a series of disconnected, isolated pools (approximately one per kilometer) has been noticed, which is resulted by loss of low flow during the dry season. Large mammals like hippos, crocodiles, and fish are crowded into these refuge areas resulting in anoxic polluted conditions and aggressive interactions (Stommel, Hofer, & East, 2016). Accordingly, terrestrial mammals are also concentrated around the remaining water, resulting in local overgrazing, particularly of riparian vegetation. This aggravates the loss of plant and erosion (See figure 2.1)
- According to a study conducted by Baker (2015), a loss of over 60% of dry season ecological habitat in the RNP is indicated as a result of the dryness of GRR. Also, the Ihefu swamp where the Great Ruaha flows from the Usangu plains lost 77% of its surface area, which implies the significant loss of wetland habitat.
- These concentrations of the game (both aquatic and terrestrial) resulted from searching for water increases aggression and the incidence of parasites and diseases (e.g. anthrax outbreak in 2003).
- The migration of hippos, birds and other animals away from the RNP to upstream areas of the river in search for water, while aquatic animals are visibly stressed from living in shrinking pools. This affects the tourism activities in the park as well.
- Animals like Hippos and buffalo are likely to be vulnerable due to changes in their environment. This is because they require regular daytime submersion in water to prevent the skin from the sun and help to regulate the body temperature. The populations of hippo are mostly affected with drought condition because of reduced conception/ fertility and mortality caused by heat stress, poor nutrition and an increase in vulnerability to diseases acquired as large number animals concentrate in a declining water resource (Stommel et al., 2016)
- The lack of water flow in the river has also been contributing to the change of behavior of some animals, such as crocodiles embarking on eating baboons.

The persistence of this seasonal dry of the river flow will result into the significant changes in the channel zones and riparian and the lack of open water areas which consequently will result in the loss of much of riverine biodiversity and breakdown of the channel morphology. The loss of dry season refugee feeding areas for terrestrial animals and increased social disruption and diseases are to be expected if the no-flow condition of the river continues.

Ultimately, if the conservation of the MGRR is not restored, the entire RNP will lose the biodiversity for which it was found hence the national, as well as international heritage value of the area, will disappear and the loss of tourism revenue.

From Fig 1, the top left photo (A) shows the elephants searching for drinking water by digging holes in the sand in the GRR bed. Photo in the top right (B) shows Hippos attempting to survive in an overcrowded, small, eutrophicated muddy water hole. The photo in the bottom left (C) indicates overgrazing of the riparian vegetation by buffaloes within the riverine vegetation close to the few remaining water holes and consequent soil erosion. The photo in the bottom right (D) shows the fish suffocating and dying from anoxia due to elevated water temperature and lack of oxygen (Kihwele et al., 2018).

Figure 2.1: Photographs describing the impacts in the RNP resulting from the cessation of the seasonal flow of GRR (Source: Kihwele et al., 2018).

2.6 Efforts expended by other researchers in addressing the challenge of water demand for ecological systems in RNP

Considering the water pressure the GRR is facing in meeting the water demand for ecological systems in the RNP, and other sectors, different efforts have been deployed by the government and non-government entities in the river basin. The target of these efforts is to find solutions to address the challenge of water demand for sustaining ecological systems in RNP. In these studies, different methodologies have been used to explore the causes, effects, and the options for restoring the flow of the GRR. These studies are:

I. Water Resources Management Guidelines in Ruaha Basin in Tanzania

This study was conducted by Mwakalila (2005) to assess the water availability in the GRR basin, the current water uses and demands in the basin as well as evaluating the current legislation regulating the water allocation and abstraction in the catchment. The study used historical hydrological and climate data, rainfall and the trend of river flow analysis, historical monthly water inflows, losses and outflows to assess the availability, uses and demands of water in the basin. The major water uses in the basin, such as irrigation, domestic, bricks making, livestock, and environmental flow, were examined.

Water uses for irrigation

The study categorized the irrigation into different groups such as traditional scheme cultivated by smallholders (T/S), improved traditional scheme cultivated by smallholders (IT/S) and improved mechanized schemes cultivated on a large scale (IM/L). The estimation of total water requirement for irrigation was done by multiplying the irrigation water requirement (IWR) with the total area under irrigation during the wet season where almost all the cultivation of the irrigated field takes place. The summary of the areas under irrigation and estimated IWR are shown in Table 2.1.

Table 2.1: Estimated Irrigation Water Requirement (IWR) for the area under irrigation

Name of irrigation scheme/ village	**Type**	**Area (ha)**	**Source of water**	**Estimated IWR (x 10^6) m^3**	**Average IWR (m^3/ha/yr.)**
Madibira state farm	IT/S	400	Ndembera river	3.3	8250
Mahango village	T/S	1000	Ndembera river	8.3	8300

a) **Water Demand for Domestic Uses**

The assessment of domestic water demand was done by reviewing the survey done by SMUWC (2001). This involved the water demand for domestic use, livestock watering and brick making as the fact that these are important dry season activities conducted in the catchment. The gross water demand for domestic use was found to be 1974m^3/day; livestock water demand was 68m^3/day while water demand for bricks making was estimated to be 43m^3/day.

b) **Environmental and Tourist Demands in the Ruaha National Park**

The study used the natural records of Msembe dated from 1958 to examine the flows at the end of most seasons. In this study, the low flow was found to lie between 1-3m^3/s. Also, the study recognized the difficulties in evaluating the demand of water for wildlife and aquatic ecological system along the river. Hence, in the absence of other information, it may be argued that the flow in the above range constitutes the demand for water in the river through RNP.

c) Water allocation and abstraction

Water resources management in Tanzania is governed by the National Water Policy of 2002 (NAWAPO, 2002) and the Water Resources Management Act 2009 (WRMA, 2009). The current act allows any person having the lawful access to any water to abstract and use water for domestic purposes provided that the abstraction activities do not involve the construction of any large-scale abstraction facilities. The abstraction of water for any other purposes requires possession of a Water Right granted by Basin Water Officers. The study conducted by Mwakalila (2003) revealed that 38% (Table 2.2) of the people abstracting the water do not have water rights.

Table 2.2: Status of Water Abstractions in the Great Ruaha basin surveyed in the year 2003

Status of abstractions	**Number**	**Percentage of the total number (%)**
With Water Rights	941	62
Without Water Rights	573	38
TOTAL	**1514**	**100**

Also, the survey pointed out that it may take a year or more before a water abstraction license is issued. The ignorance of people regarding the requirements of water rights and awkward procedures which the applicant needs to go through before being granted the water right was found to be the cause of illegal water abstraction.

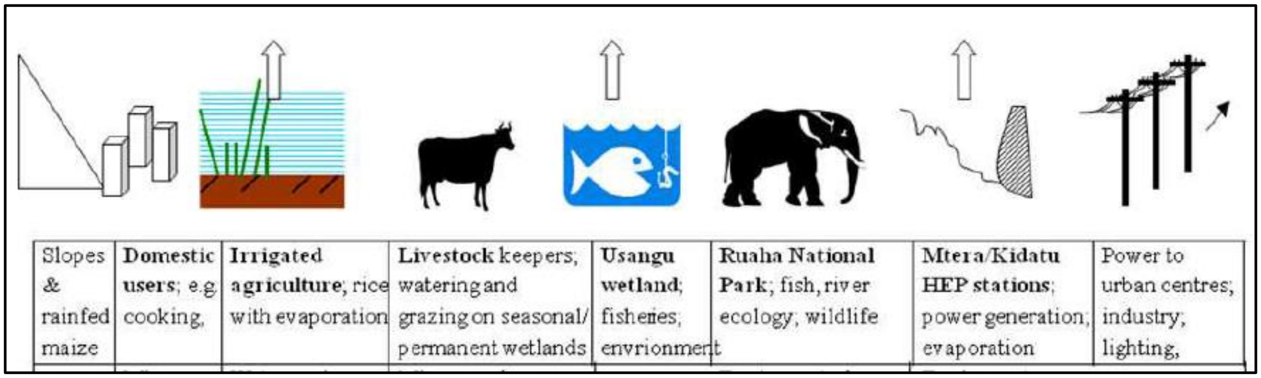


Figure 2.2: Water use sectors in the Great Ruaha River (Source: Lankford et al., 2004)

II. Environmental Flow Assessment: The Great Ruaha River and Ihefu Wetlands, Tanzania, and options for the restoration of dry season flows

The objective of the study was to determine the required inflows into the eastern Usangu wetland to meet the recommended flow rates downstream, in the RNP. The study was also aimed to evaluate the response of the wetland to changing flow regimes, not only those caused by upstream abstraction, but also for proposed engineering modifications, i.e., the construction of the Lugoda Dam, and the Ndembera transfer option.

Among the issues assessed in this study were, identification of water use for irrigated rice agriculture in Usangu plains that was considered as the predominant factor for seasonal reduction of flow in the Ihefu swamp and cessation of dry season flows in the GRR downstream of Ihefu (N'Giriama). These options were analyzed and screened based on their feasibility and implement-ability to achieve the targeted objectives.

a) **Technical options** (engineering-based options that require the construction of infrastructure)

In this category, the options explored were:

1. **Storage options** (**Construction of the Lugoda Dam)**.

From the preliminary studies conducted, the dam will have a storage capacity of dam 351.7 MCM with a height of 36m and an inundated area of about 61square km. The option of supplying the wetland with flows from the proposed Lugoda reservoir (to be located on the Ndembera River) was explored. The investigation was critically based on the drought low flow conditions, so as to achieve an adequate flow during drought low flow conditions.

Thus, the study found that an outflow discharge of $2m^3/s$ at N'Giriama was investigated by computing the total daily outflows from the Ihefu wetlands that must be balanced by the total inflow into the wetlands to ensure the availability of at least $1m^3/s$ to RNP**.** At the presumed existing flow regime of the GRR at Nyaluhanga, it was found that an inflow of at least 6.81 m^3/s should enter the eastern wetland (Ihefu) to account for within the reach system losses and supply an outflow of 1-2 m^3/s past N'Giriama. This flow has to be provided from the reservoir to the wetlands during zero inflows of the GRR at Nyaluhanga, to sustain the EFR at RNP

2. **Transfer options (from Ndembera river)**

The option of transferring water from Ndembera river to GRR was found to achieve the objective of restoring the flow to the GRR. This is because the transfer will require simple construction design (a diversion weir directing into transfer canal or pipeline). Besides, the distance from the diversion point (Ndembera river) to GRR was found to be relatively short (about 25km), which further support the option. Ndembera river was found to have sufficient flow to support 1m^3/s flow requirement in the GRR during the dry season. The transfer option was found to be viable because the transfer mechanism does not require any storage facility to enhance the flow during the late dry season. Moreover, this option was recommended to be economically feasible only if the transfer will also serve to small scale irrigated agriculture and domestic water use.

b) **Institutional options** (Management of the resource through the development of particular institutional arrangements and use of WRM instruments)

Achieving the restoration of water flow in the GRR depends much on the management of the water resources system. Though this has not quantifiable amount to be saved through appropriate institutional arrangements, the fact that some water is being lost in the systems that are fully compliant and controlled, a conceptual level shows that proper water resource management in the Usangu plains can result in the objectives of restoring the flow in the GRR.

To achieve this, the study found that there is a need of having a good understanding of the water availability and water use, appropriate water allocations planning and mechanisms, good water licensing and compliance, water pricing as well as cost recovery of the water resources management in the basin.

Hence, the sustainability of the water resources management in Usangu plain and GRR, in general, will entirely depend on the strength of the institutions and availability of the requisite capacity of human resources, infrastructure, and financial capacity building. This will be achieved through having adequate water pricing and cost recovery mechanism together with engaging donor and government to raise the financial capacity of the institute.

III. **Tanzania 2001 SMUWC Usangu basin irrigation** (Sustainable Management of the Usangu Wetland and its Catchment)

This study aimed at addressing the current hydrologic conditions of Usangu wetlands. The study used the natural flow records dated from 1958 at Msembe to assess the water demand for the environment and tourism in the RNP. The low flow condition at the end of the dry seasons was found to range between 1-3m^3/s, which was found to be influenced by occasional dry up of the river due to natural conditions (Figure 2.3).

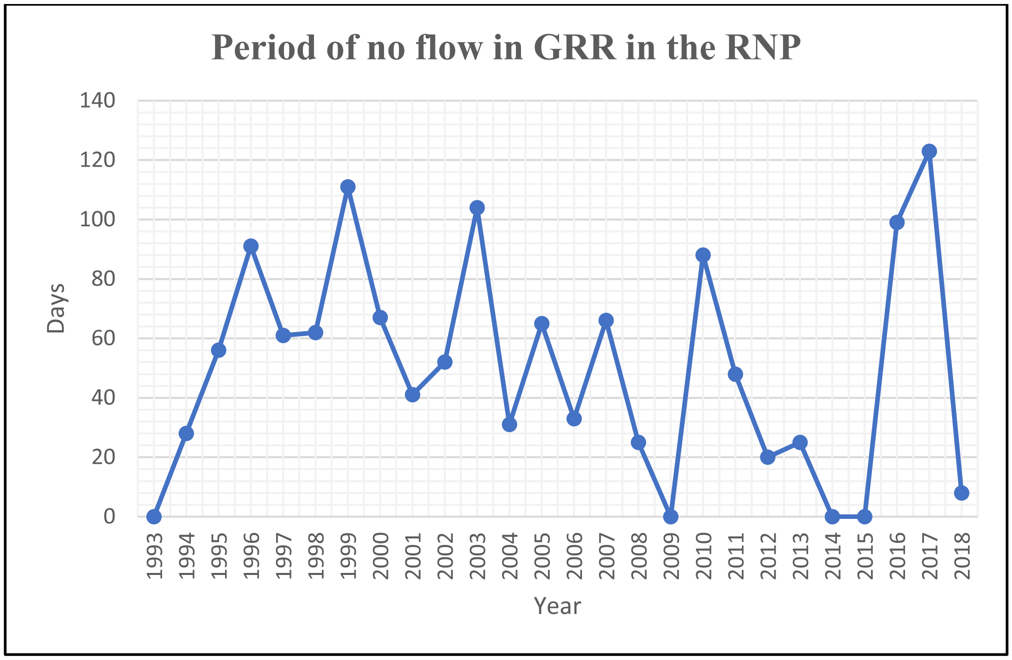


Figure 2.3: Periods of no flow in Great Ruaha River in the RNP

Additionally, the study used historical climate data (records of over 30 years) to evaluate the potential evapotranspiration of different irrigation schemes established in the catchment. The monthly values of potential evapotranspiration from Madibira station, which represented the eastern wetland were found to have a total of 1901 (Penman).

Moreover, the assessment of the water balance of the eastern wetland was done by involving the Madibira smallholder agriculture development project, which was established in 1998.

In this study, it was discovered that using the cropping calendar and water application rates contained in the design manual of the project, the estimate of 450ha will require 7Mm^3, an area of 1800ha will need 29Mm^3 of water while 3000ha will need 49Mm^3. This is equivalent to an average of 16000 m^3/ha/yr. The study used these values of gross demand to subtract with the observed natural flow of the Ndembera river at Madibira to give the net volume of water inflowing to the northeastern part of the wetland.

This study showed that the construction of a reservoir in the main river (Ndembera) flowing down from high catchment would help to store water from flood flows during the wet season and release this water during the dry season. The detailed analyses of this reservoir are shown in Table 2.3.

Table 2.3: Regulating reservoirs proposed for the perennial rivers

Reservoir	River	Mean annual inflow (M^3/s)	Mean regulated outflow (M^3/s)	Operational reservoir capacity (Mm^3)
Lugoda	Ndembera	6.0	4.0	210

IV. Environmental Flow Assessment of Great Ruaha River in Southwestern Part of Tanzania

This study was conducted by Mwakalila & Masolwa (2012) to determine the flows necessary to maintain or restore riverine conditions in the Middle GRR (MGRR) in the RNP, between Ng’iriama and the Mtera Dam **(**Figure 2.4).

The study used the building block method to identify a series of essential flows for the aspects of the natural hydrological regime that ensure the sustainability of the ecosystems in the basin. The study found that a total inflow into the eastern wetland of 5.52-6.81 m^3/s is required to provide outflow of 1-2 m^3/s past N’giriama and hence meet the dry season low flow in the RNP. Moreover, the study recommended the 2.5 m^3/s and 19 m^3/s to be flowing in the river during driest and wettest months respectively.

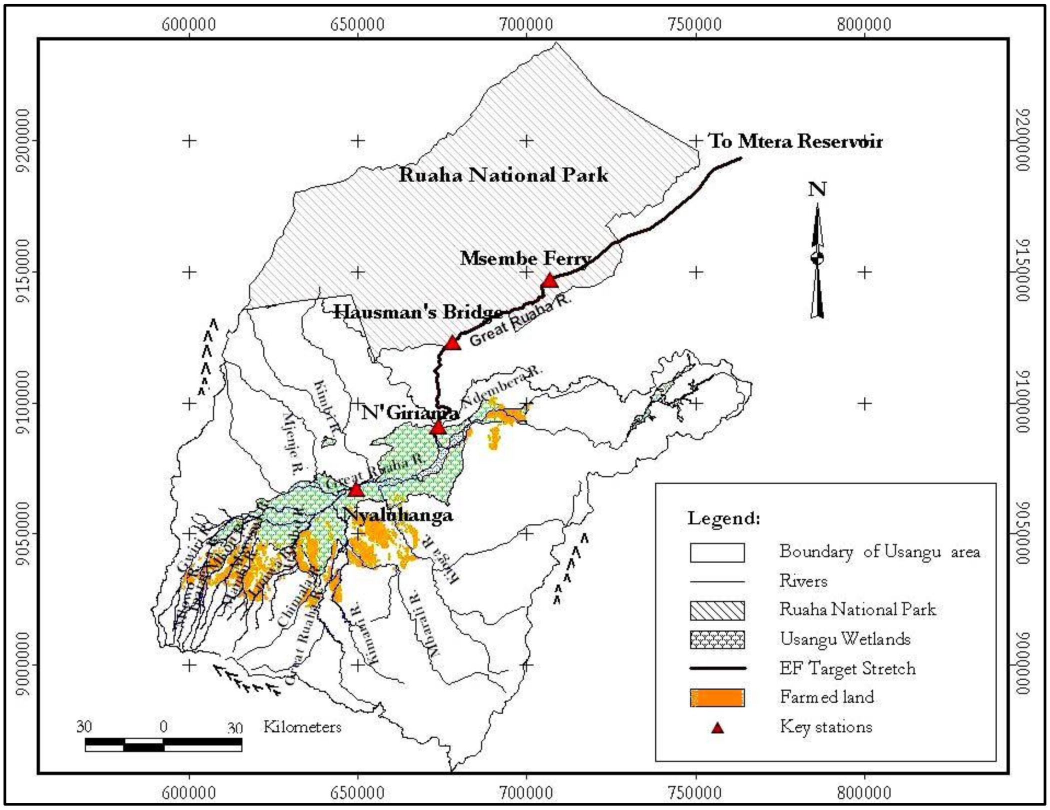


Figure 2.4: Great Ruaha River basin (Source: Mwakalila, 2011)

2.7 Methods of Environmental Flow Assessment

For ensuring that the riverine ecosystems remain healthy and provide benefits to the people, the river must have water, debris, and sediments. Thorough management of river flow, river damming, and reservoir or abstraction of water for irrigation and industrial activities can devastate the ecosystems and livelihood downstream (Mwakalila & Masolwa, 2012). A holistic consensus-based decision on the development of water infrastructures can provide an integrated flow in the river management for ecosystems, livelihood energy, and agricultural activities within the limits of available supply and under a changing climate.

Globally, the maintenance of the health of the river's ecosystem through estimation of ecological and environmental flows has been conducted using different methodologies (Arthington, 2002).

Hydrological method (Average Base Flow) is one of the methods used in estimating the environmental flows of the river. The methods use hydrological data (historical monthly or daily flow records) for making environmental flow recommendations for maintaining river health at a designated level (Vélez et al., 2015).

2.8 Options to Modify Releases from Dams and Reservoirs

Worldwide, there are several ways of modifying the environmental flow. However, the dams are frequently the major and direct modifiers of the natural river flows and the starting point for improving environmental flows (Smakhtin and Anputhas, 2006).

The release of water from the dam to the downstream area is broadly determined by the physical provisions to pass the water through, around or over the dam. Also, the policies used to operate the dams influences the release of water stored in the reservoir behind the dam as well as demand schedules for the competing water demand sectors like ecological flow, hydropower generation, irrigation and domestic water demand (Bhattacharjee, 2014). Moreover, to achieve sustainable development goals (6, 13, and 15), the principle of integrated water resources management has to be employed where environmental, and social-economic factors have to be engaged in the decision making.

The Great Ruaha River is one of the most important rivers in the Rufiji basin found in Tanzania. This river is vital for the generation of hydropower production, irrigation, water supply to rural households. The water from the river contributes to the livelihoods of the ecosystem in RNP as one of the significant wildlife reserves (Kashaigili et al., 2006). To ensure equity, environmental protection, development priorities, balancing supply and demands and promoting the efficient use of water in response to the scarcity of water resources, the proper allocations of water available has to be undertaken objectively (Ayele, 2016).

The Decision Support System (DSS) has been used by different studies to allocate water resources between the competing water users and analyzing the water balance of the river basins (Okungu et al., 2017).

WEAP21 is one of the water allocations models, which mainly follow a priority rule of the allocations of water resources to the different water users (Sieber & Purkey, 2015).

2.8.1 Introduction to WEAP model

The Water evaluation Analysis and planning (WEAP) was first developed by the Stockholm Environment Institute’s US Center (SEI-US) in 1990. Due to significant advances from the previous version, the current version is officially labeled as WEAP21 (Kerim et al., 2016). The WEAP model is a scenarios-based decision support system (DSS) that attempts to combine an integrated modeling tool for water resources planning and management with a range of conceptionally simple models for watershed hydrology (Jariwala & Vadher, 2016).

The arrangement of this tool is distinctive in that it incorporates the physical hydrological processes of a system with the management of the institutions and infrastructures governing the allocation of water resources (Vogel et al., 2007). This model facilitates a comprehensive, flexible, and user-friendly framework for the development of water resources management (Chuthamat, 2016). The engineering and biophysical components of the systems facilitate a multi-stakeholders water management analysis on a broad range of topics including reservoir operations for ecosystem water requirements, rainfall-runoff, base flow and groundwater recharge from precipitation (Ayele, 2016; Yaqob et al., 2015).

The tool is also used to develop water balances, scenario generation, planning, reservoir operations, hydropower generation, water conservation, pollution tracking, and water quality, vulnerability assessments and policy analyses (Homa et al., 2005). Moreover, as a policy analysis tool, the model has been used by numerous studies to evaluate a wide-range of water development and management options and takes into account multiple and competing uses of water systems (Yates et al., 2005).

Water balance in the WEAP model depends entirely on the climate, hydrological data, water supply, and demand data so as to map the existing water resources and users within the basin and to allocate the abstraction and discharge of water (Mohamed & Ali, 2012).

From the first month of the current account year to the last month of the last scenario year, WEAP21 operates based on a monthly time series. These months are independent of each other (i.e. the current month does not depend on the previous month), except for the reservoir and aquifer storage (Richter & Thomas, 2007). The water balance in the system can be natural or influenced by human activities. The monthly water entering the system (e.g. groundwater recharge, runoff into reaches or head flow) can either stored in an aquifer, reservoir or leaves the system by the end of the month through transmission and return flow link losses, evaporation, demand site consumption, or outflow from the end of the river (Zeiringer et al., 2018). Also, these links are used to convey the wastewater from the treatment plants or wastewater outflow to the demand sites for reuse or recycling (Vogel et al., 2007). In this case, WEAP uses the user-defined system to determine the water allocation along with each transmission link in each month (Richter & Thomas, 2007).

WEAP21 is structured as a set of five different "views" of your area. These views are divided according to their functionalities, such as data inputs, data analysis, data view, scenarios analysis results view and notes for different processes used (SEI, 2015). The model is also used to generate the flow duration curves of the river based on different time steps such as the daily, weekly and monthly stream flows for a particular river basin (Berhe, 2013). The FDC is used to provide an estimate of the percentage of the time given streamflow was equaled or exceeded over the historical period (Assata, 2008).

2.8.1.1 WEAP basic tools

Data

In WEAP, the data view is the place where the user can create the data structure, models, and assumptions. In this view, the screen is divided into four parts: the top left part is used for the hierarchical tree to create and organize data structures under six major categories key assumptions; demand sites, hydrology, supply and resources, environmental and other assumptions (SEI, 2015). The right screen is used for choosing the data to be edited. The bottom left screen is used as a data insert schematic in which by clicking the element in the schematic, it will result in a jump to its place on the tree. The data entry table found in the top right of the screen is used to edit and create modeling relationships. The data or information entered in this screen is displayed graphically in the bottom right panel of the screen (Berhe, 2013).

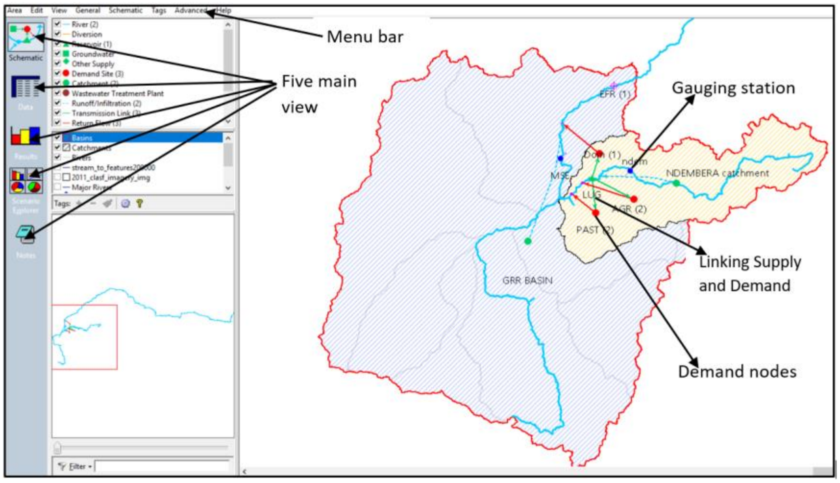


Figure 2.5: WEAP views and its schematic view of GRR catchment

Results

This tool is used to show a wide range of charts and tables covering different aspects of the system like supply, demand, environmental loadings, and costs. The display of the customized report can also be viewed for one or more scenarios in this view. Moreover, the “favorite” option can be used to bookmark the most useful charts for the analysis.

Scenarios explorer

In WEAP, the explorer view is used to group the “favorite” charts which were formed previously in the “results” view into “overviews” for concurrent display. The scenario explorer view can also be used to display the data across many scenarios as well as helping to demonstrate the impact of various assumptions and policies on the results. Also, this view allows to change the input values on the spot and WEAP will recalculate and update the results.

Catchments

Catchment can be defined as hydrological area collecting the water within a given drainage divide (drainage divides are lines. which separates adjacent drainage basins). The catchments for all the tributaries of the river are taken together to form a river basin (Zeiringer et al., 2018). The watershed can also be the area defined by a user within the schematic where you can specify the processes such as precipitation, evapotranspiration, and runoff of ice melt.

Rivers, Diversions and River Nodes

The rivers and diversions in WEAP software are made up of nodes which are connected by the river reaches. These river nodes are categorized into seven types:

Reservoir nodes,

These represent reservoir sites on a river. This node used to release the water from the river reservoir directly to the demand sites or for use downstream. This can also be used to simulate the hydroelectric power generation.

Flow requirement nodes,

These nodes are used to define the minimum instream flow needed at a point on the river or diversion to meet water quality, fish and wildlife, recreation, and downstream requirements.

Streamflow gauges,

These are the nodes used to indicate the places where the actual measurements have been taken. These nodes are also used as a point of comparison between the actual streamflow and simulated flows of the river.

Transmission Links

The surface water (reservoir nodes, abstraction nodes), groundwater, and other sources of water supply are transferred to the demand sites through transmission link. Also, these links are used to convey the wastewater from the treatment plants or wastewater outflow to the demand sites for reuse or recycling. In this case, WEAP uses the user-defined system to determine the water allocation along with each transmission link in each month (Droogers, 2009).

Runoff/Infiltration Links

Catchment Runoff/ infiltration link is the water from the precipitation, irrigation and soil moisture storage that has not been used up by evapotranspiration or losses to increased soil moisture. The runoff/infiltration links carry the runoff and infiltration water from the catchment to the river, reservoir, groundwater nodes, and any other water sources. These runoff/infiltration links are also used as headflow to the river (Droogers, 2009).

Return Flow Links

The return flow links are used to convey the water that is not used at a demand site and being directed to the other demand sites; wastewater treatment plants surface water and groundwater nodes. The water conveyed can be taken to rivers nodes, local supply sources or other demand sites (quantified in the percentage of discharge).

2.8.1.2 Application of Water Evaluation and Planning (WEAP)

The WEAP model has been widely used for various river basin studies in the world. This model has shown the effectiveness of supporting the decision-makers to allocate water resources, especially in basins with high water use competition. Below are some examples of the studies conducted using the WEAP model.

Niger River basin

The Niger River basin (NRB) is a transboundary watershed in West Africa shared by nine countries, including Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Niger, and Nigeria. The basin constitutes of different water competing activities such as biosphere reserve, irrigation, farming, fishing, the growing industrial activities, livestock activities, and parks with a variety of wildlife.

Due to economic, socio-cultural, and ecological issues involved in the basin, the management of water resources had become more complicated. The study involved the WEAP model in optimizing the allocation of present and future water resources in the Niger river between the competing water demands (Mounir, 2014). The study involved different scenarios such as population increase in the areas which are under constant water supply, the climate change to abnormal climatic conditions and the use of water year method while dealing with change in climatic conditions.

The study analysis found that the increased water demand caused by a growing population couldn't be met. Thus, it was recommended to construct a hydropower dam which will help to control the flow of water and low levels in the river to provide sufficient water supply for the towns facing the shortage in 2030.

Caledon River

The Caledon River is a transboundary river shared between the Republic of South Africa (RSA) and the Kingdom of Lesotho. The river has a catchment area of 22 127.73 km^{2,} of which 69%

of the area is in South Africa, and the remaining 21% is in Lesotho (Ayele, 2016). The catchment area has been facing high water demands due to high population depending on the water from the river. Also, the river experiences periodic water scarcity, which in turn increases the water demand for urban and peri-urban areas.

Ayele (2016) conducted a study to assess future water demands and water balance by using the WEAP model. In this study, the assessment of future water demands was evaluated by involving various scenarios such as increased irrigation activity in Lesotho, high population growth, and the implementation of environmental flow requirements (EFRs).

The modeling framework of this research work found that the projected demands will not fully be met, and water supply coverage will be decreasing over time. The catchment will face the water scarcity due to increasing water demand caused by population growth and urbanization and implementation of environmental flow requirements. This implies that the application of EFRs will help to secure more river flow by compromising the availability of water for human demands.

Hence, the study helped to inform the decision-makers on the future water resource management planning in the catchment by indicating that other sources of water should be considered to meet the demands.

Based on those factors, it was found that the WEAP model is preferable to be used for simulating the water supply and demand for allocations within Ndembera river catchment and RNP.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1. Introduction to Materials and Methods

This chapter describes the methods and procedures used in the research work. The chapter focuses on the demographic and hydrological characteristics of the study area, preparation of data inputs, conceptual modeling, and the scenario developments. In this study, WEAP21 represents two supply sources, which are; dam discharge and the water runoff after the dam catchment area. Accordingly, the chapter discusses the processes that were used to calibrate the model, validate as well as analyzing the scenarios.

3.2 Description of the Study Area

3.2.1 Geography

Ndembera River is one of the rivers which flows into the Great Ruaha River throughout the year. The river has a catchment area of about 3190 square km. The catchment extends between three districts which are Mufindi and Iringa from Iringa region and Mbarali from Mbeya region.

The Ndembera river originates from the springs of Udumka village at an elevation of about 2060m (a.m s. l). It is located between latitudes 7°57”09’S and 8°13”25’S and longitudes 35°05”16’E and 35°37”49’E (See Figure.3.6). The river catchment is located in Usangu Basin, in the southern highlands of Tanzania (Kangalawe, Mwakalila, & Masolwa, 2011a).

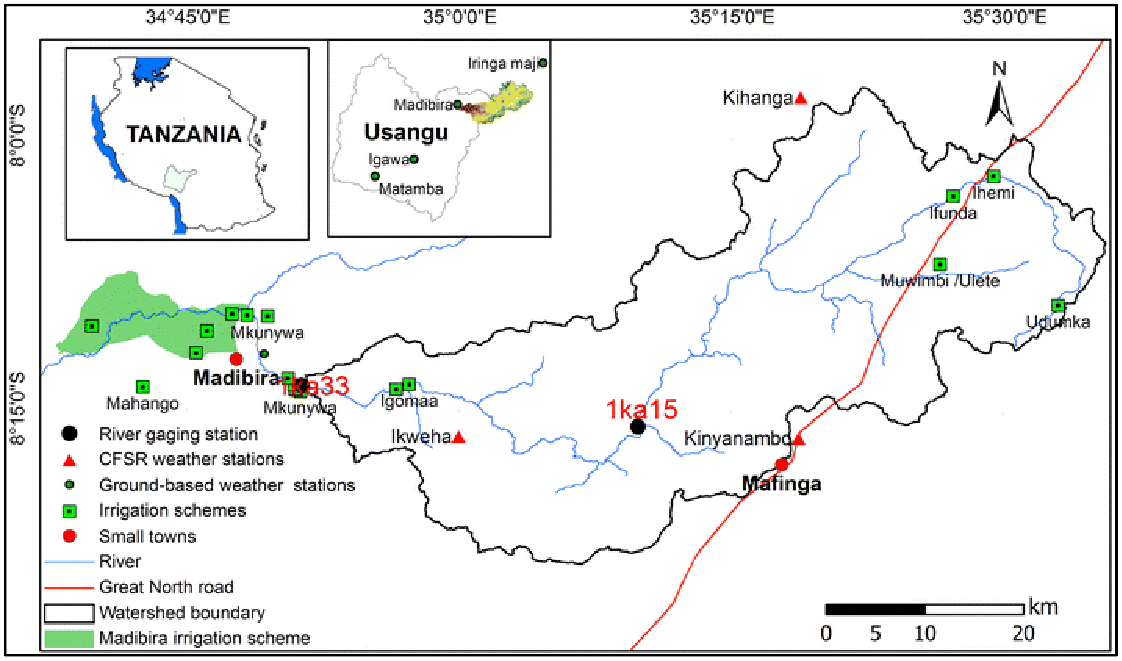


Figure 3.6: The Location of Ndembera river catchment within the Iringa Region in Tanzania (Source: Kangalawe et al., 2011a)

Other perennial tributaries which contribute its water to the Great Ruaha River are Chimala, Ruaha, Kimani, and Mbarali (Hyandye et al., 2018). The water flow of the river discharges its water to the Great Ruaha River and accounting for about 15% of the total flow of the GRR. The natural wetlands of this valley include highland grasslands, swamps, streams, and rivers. The major land-use types or classes are bushland, cultivated land, grassland, swamps, floodplains, open waters, forests, settlements, and woodland. The Ndembera river has been used for different activities such as large-scale agriculture in villages like Igoma, Mahango, Ifunda, Muwindi, Ihemi, Madibira, and Mkunywa.

However, in order to understand the study of water ecological water demand in Ruaha National Park (RNP), it is essential to understand the flow condition of the Great Ruaha River (GRR). The Great Ruaha River basin found between longitudes 34° and 36° E and latitudes 6° and 9° S. The Ndembera river confluence with GRR at Ihefu plains then flows to the N'Giriama. Also, the GRR flows to the Ruaha National Park which is 30km downstream of N'Giriama then flows to Mtera dam. The basin covers an area of about 68,000km^2 upstream of the Mtera reservoir. The river continues southwards and flows across the Selous Game Reserve before reaching the Rufiji River (Figure 3.7).

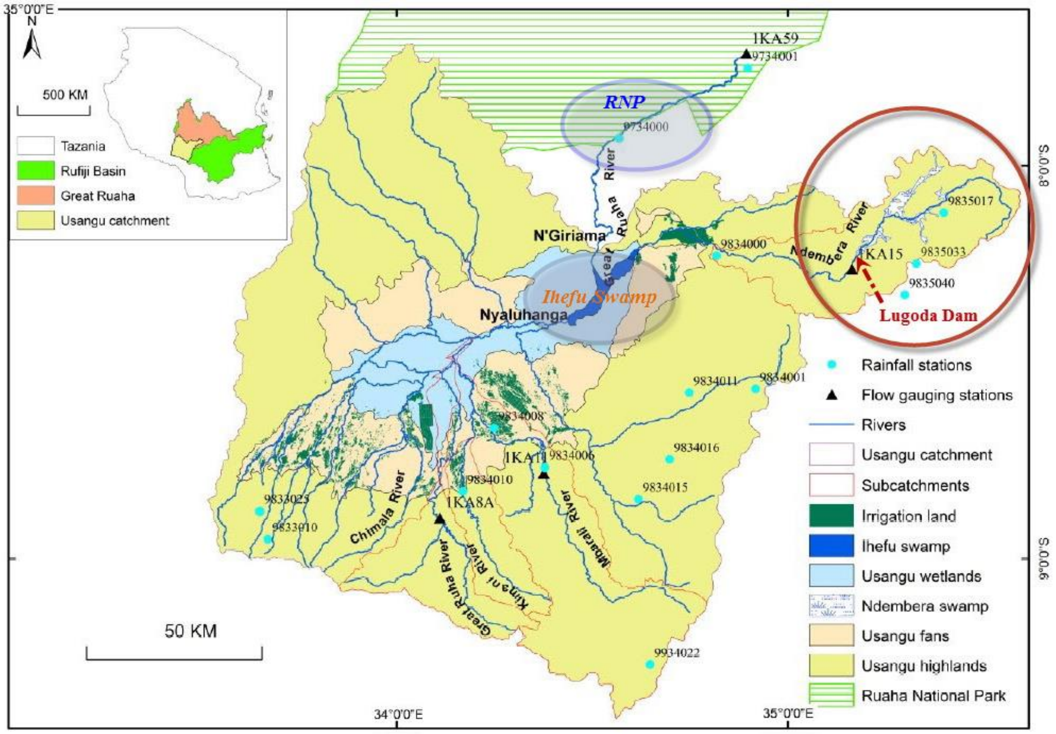


Figure 3.7: The Great Ruaha River catchment (Source: WWF, 2010)

3.2.2 Climate of the area

The basin experiences a seasonal climate: the wet period which begins early of November to the end of April and the dry period, which starts on may to the end of October. The precipitation of the catchment is uni-modal, whereby the highland areas receive rainfall of about 1600mm/year, while the plains receive about 500-700mm/year with mean annual discharge is 140 m^3/s. (Zeiringer et al., 2018). The low temperature ranges between 15°C - 18°C up to 32°C in October to December. From January to May, the temperature ranges between 15°C to 19°C while from June to September it is around 15°C (Timiza, 2011). As shown in Figure. 3.8, the monthly average evapotranspiration is higher than rainfall throughout a year except for February. This indicates the importance of irrigation water for rice growth and maturity.

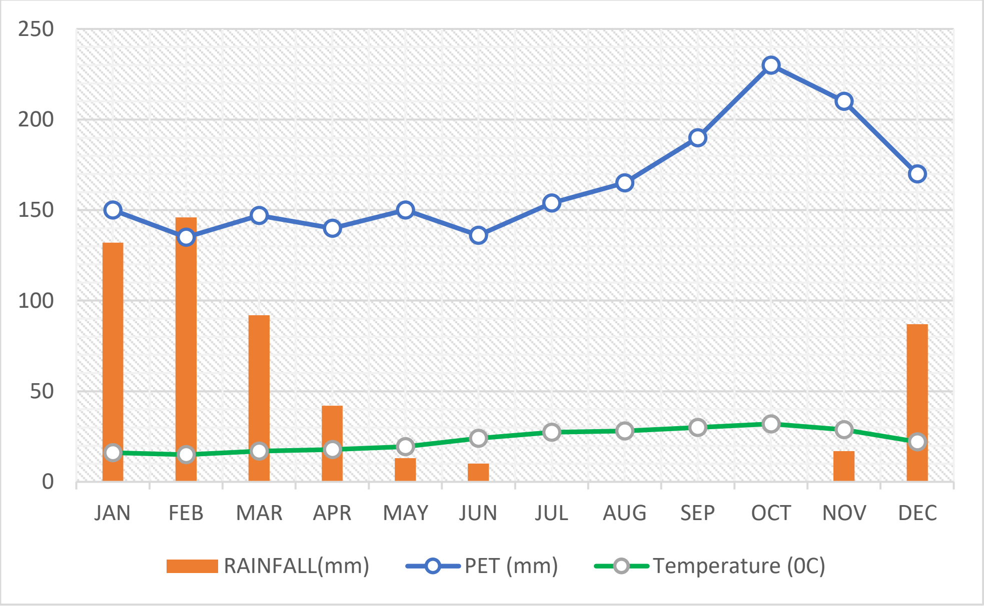


Figure 3.8: Monthly average rainfall, Potential evapotranspiration (PET) and Temperature GRR basin from 1990-2018 (Source: RBWO)

3.2.3 Population

The Ndembera catchment (Madibira) has a population of about 32 693 people (15 764 males and 16 929 females) (National Bureau of Statistics, 2013). The community is almost homogeneous and is comprised of Hehe, Kinga, and Bena among major ethnic groups. The average annual population growth rate is 2.2% (NBS, 2013).

3.2.4 Land use and land cover

The area has a variety of land cover, use and vegetation patterns from the highlands to the lowlands. While the highlands (except in high altitudes) are naturally dominated by miombo woodland, the lowlands (below 1100m a.m.s.l) are typically divided into two parts which are wetlands and fans (Kangalawe, Mwakalila, & Masolwa, 2011b). The wetlands consist of seasonal flooded open grassland, seasonal woodlands, and small perennial flooded swamp (Ihefu). The Ihefu swamp has a coverage area of about 80km^2 composed of five large ponds, namely; Nyankokolo, Ruaha, Lyang’ulage, Nyamwono, and Marihemu. The swamp is generally comprised of water lilies and floating water chestnut. Moreover, these swamps act as water flow regulator to downstream of the Usangu plain.

The fans composed of alluvial deposits spread from the base of the escapement onto the plains are extensively cultivated due to its fertility. The higher altitude (> 2000m a.m.s.l), there is humid forest and Alphine grasslands (Mwakalila, 2011). Accordingly, some parts of the basin are also used for settlements along the rivers and in large-scale farms and irrigation schemes located at Mahango, Igomaa, Muwimbi, Mkunywa, Ifunda, Ihemi, Udumka villages and Madibira town (Hyandye et al., 2018). Generally, the plain helps 95% of the households found in the basin benefits from agricultural activities, small scale bricks making industries, traditional fisheries, and cattle grazing.

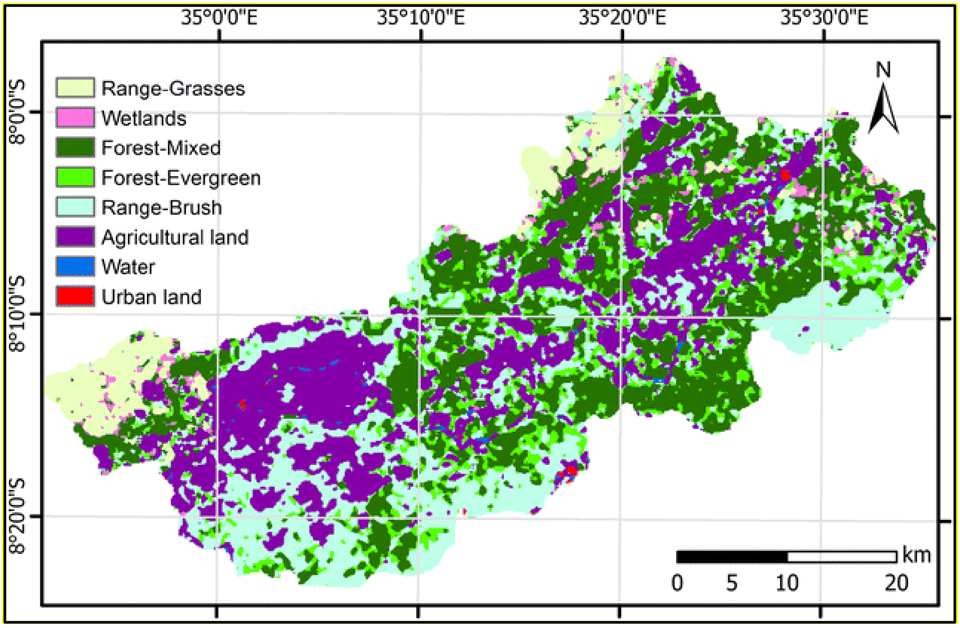


Figure 3.9: Land use/cover of Ndembera river catchment (Source: Hyandye et al., 2018)

3.3 Research Design

This research was designed as illustrated in Figure 3.10

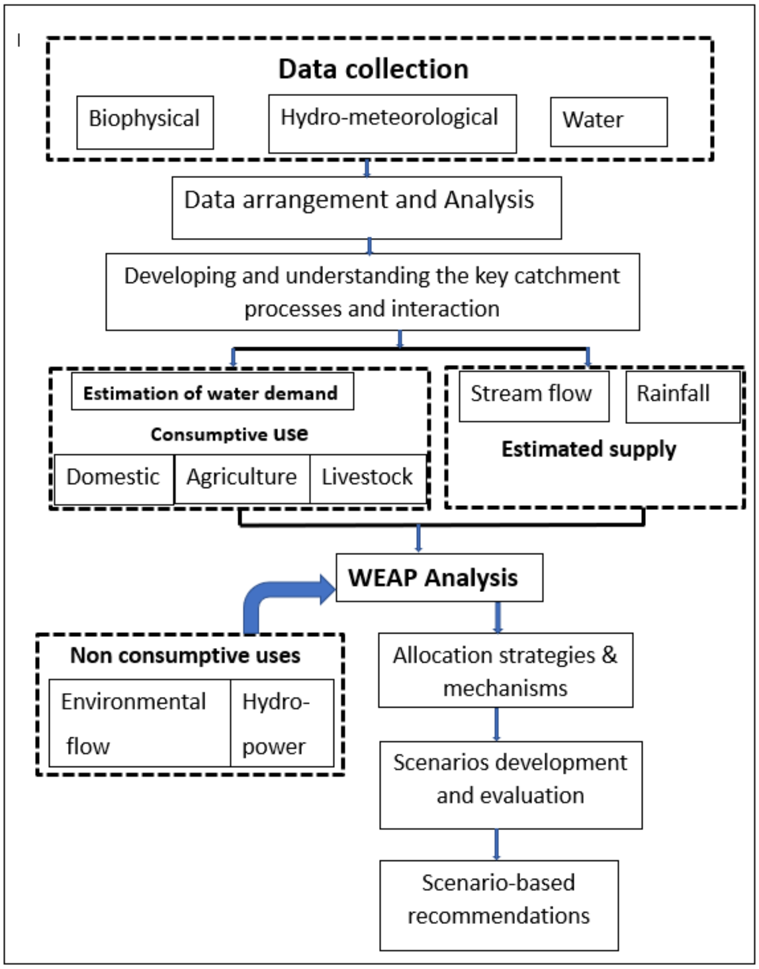


Figure 3.10: Conceptual Framework (based on Tesfamariam, 2018)

In this study, the water availability was assessed based on the water Lugoda dam to be built in the Ndembera river basin (a tributary of GRR) and the GRR discharge from Nyaluhanga through N’Giriama to RNP. Accordingly, the factors like rainfed supplies and other aspects affecting the supply were taken care using variations in annual activity levels, monthly variations, consumptions rates, annual water use rate, loses and the reuse of the stream water.

3.4 Data Collection

The important data for this research were obtained in different ways; by visiting the government institutions responsible for watershed management and water users as well as conducting Key Informant Interviews to official stakeholders of the GRR basin.

The population data was fundamental in establishing the demand and was obtained from the Tanzania National Bureau of Statistics (NBS). The per-capital water demand for the various demand levels was based on the Ministry of Water and Irrigation Design Manual (MoW, 2003)

Irrigation data and streamflow data were obtained from Rufiji Water Basin Offices (RWBO), Iringa Municipal council and department of land use planning and management (Agriculture offices) under the ministry of agriculture, livestock and fisheries. The rainfall temperature and evapotranspiration data of the Ndembera River, GRR basin and its tributaries were obtained from RBWO. The future development plans in agriculture and other water use sectors were obtained from the Madibira Agricultural Marketing Cooperative Society.

The review of different studies conducted in the basin has been done to get insight information, methodologies used, and see the gap to be filled. Besides, shapefiles of Digital Elevation Model (DEM) of various characteristics were used in the ArcGIS software to generate the boundaries and showing other characteristic features of the study area. The generated shapefiles were uploaded into WEAP software to be used for a systematic view of the case study.

Various important water supply elements were chosen strategically within the river reach, including main tributaries, swamps, reservoirs and groundwater which were then considered in the study for the entire basin. The towns, rural areas, irrigation areas, environmental flow, and institutions were treated with nodes as water demand sites. While the transmission links were generated between the rivers and respective demand sites, the return link was used to link back the flow from the demand sites to the river course.

3.5 Data Analysis

The study used WEAP model version 2019.10.20 to analyze the data and allocate the surface water available for different water demand sites (e.g., Madibira, EFR, domestic demand, brick making, livestock demand) found within the GRR basin for the period between 2019 and 2050.

Model Development

The evaluation and analysis of surface water resources available in Ndembera River Basin and GRR Basin were done by WEAP model based on the observed river flow of 2 gauging stations: i) 1KA15 (Madibira), and 1K59 (Msembe ferry). At all the stations, river gauging data were obtained for 1971 – 2018 (Figure 3.6). The daily river flow and annual water resources available were obtained using WEAP system based on flow data as an input.

Modeling Current and Future Water Demands among water users

WEAP model was used to analyze the current and future water demands for environmental flow, agriculture (irrigation) and domestic (including industrial, commercial, and institutional). In order to analyze the current water demand situation and scenarios of the catchment, various steps were followed. These steps are as follows:

i. Definition of the study area and time frame

Arc GIS 10.3 was used to prepare the vector layer which defines the study area and its boundaries then added to the WEAP system. This was done considering that WEAP reads vector shapefiles formats of WGS 1984 projection. In addition, due to availability of the current, projected and planned development in the basin to all water sectors, a 30-year period was set from 2019 and the last year of the scenario was set to be 2050.

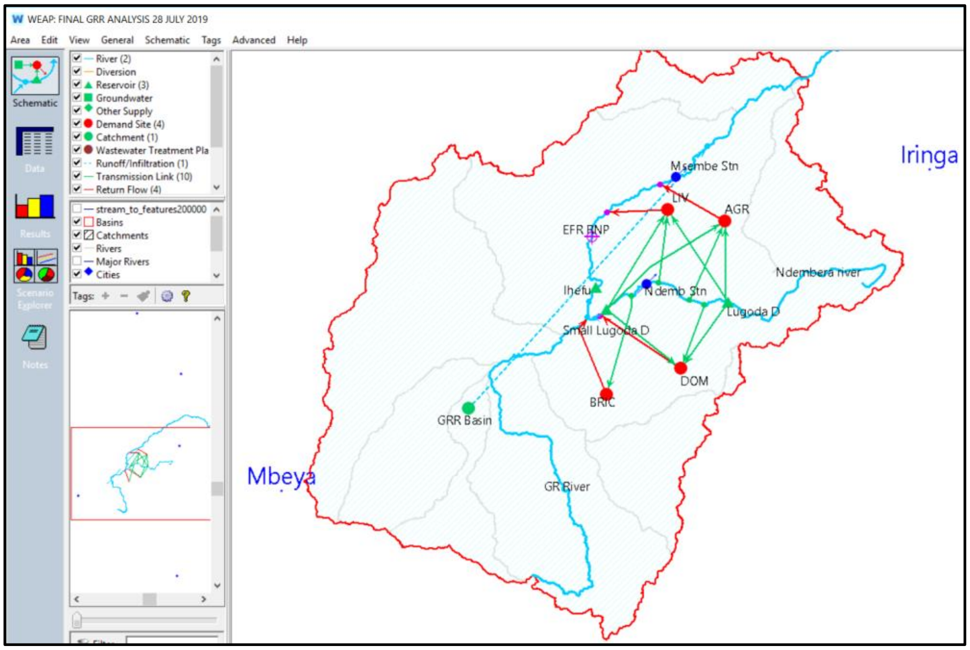


Figure 3.11: Great Ruaha river basin delineated area of study

ii. Creation of the current accounts

In order to form the basis of the entire modeling, it was important to create the current account of the catchment. This involved specifying the existing water resources as well as available demand nodes. Besides, this account was used for the calibration of the model to adapt to the existing situation of the case study area. The current accounts were assumed as starting year for all scenarios which are used as the basis for projections. Moreover, the supply and demand were defined for the first year of the study (2018) on a monthly basis (January-December). The input data used in this current account involved all the collected current information for water supply as well as water demands.

iii. Creation of scenarios

Creation of scenarios was based on future assumptions and expected an increase in numerous indicators which helped to center functioning of the WEAP model. This allows possible water resources management processes to be adopted from the results generated for running the model.

iv. Scenarios evaluation

WEAP used scenarios as a way to evaluate different water allocation schemes, given water demand and associated priorities. Based on the availability of the water resources in the study area, the results generated from the creation of scenarios would help the water resources planners in decision making, which is the core of this study. In order to avoid the water-based conflicts among water users, all the scenarios were evaluated and the possible solutions were listed down. This also included the listing down the potential suggestions and strategies for balancing the water supply and demands.

3.6 Platform of the WEAP Program

Demand Sites

A demand site can be defined as a group of water users that share a physical distribution system, that is all within a defined region or that share a vital withdrawal supply point. In this site, the user can lump demands together into aggregate demand sites or to separate the key water uses into individual water demand sites (Assata, 2008).

The demand site is the comprehensive tool which is used to define the actual physical infrastructure, such as pumping stations and withdrawal facilities. so, this is the site where a user needs to carefully configure the entire demand and supply system which includes the links between supplies and requirements (Chuthamat, 2016).

The demand sites were used to define the different groups of water users such as agriculture, domestic water users, pastoralism, brick making industry, and environmental water demand. The demand sites were connected by transmission link from its water sources and where applicable, a return link either directly to the river, wastewater treatment plants or other location (Vogel et al., 2007).

The targeted rivers were digitized, starting from a source going downstream. Head flow data at a gauging station were entered using the WEAP schematic view. These data include minimum environmental flow requirement to meet the ecological needs, return flow, stream gauge and transmission link for demand sites and supply sources.

These demands sites were also entered at the schematic view. The demand priorities were set based on the NAWAPO (2002).

Demand sites with the highest priorities would be supplied first. For each demand site, the Annual Activity Level, Annual Water Use Rate and Consumption were entered to be used in calculating the water demand. Different levels of disaggregation were created for each demand site, for example, (i) Domestic Water Demand (DOM), (ii) Agriculture Water Demand (AGR), (iii) Brick making Water Demand (BRIC) (iv) Livestock watering (LIV), and (v) Environmental Flow Requirement (EFR) as shown the Figure 3.12:

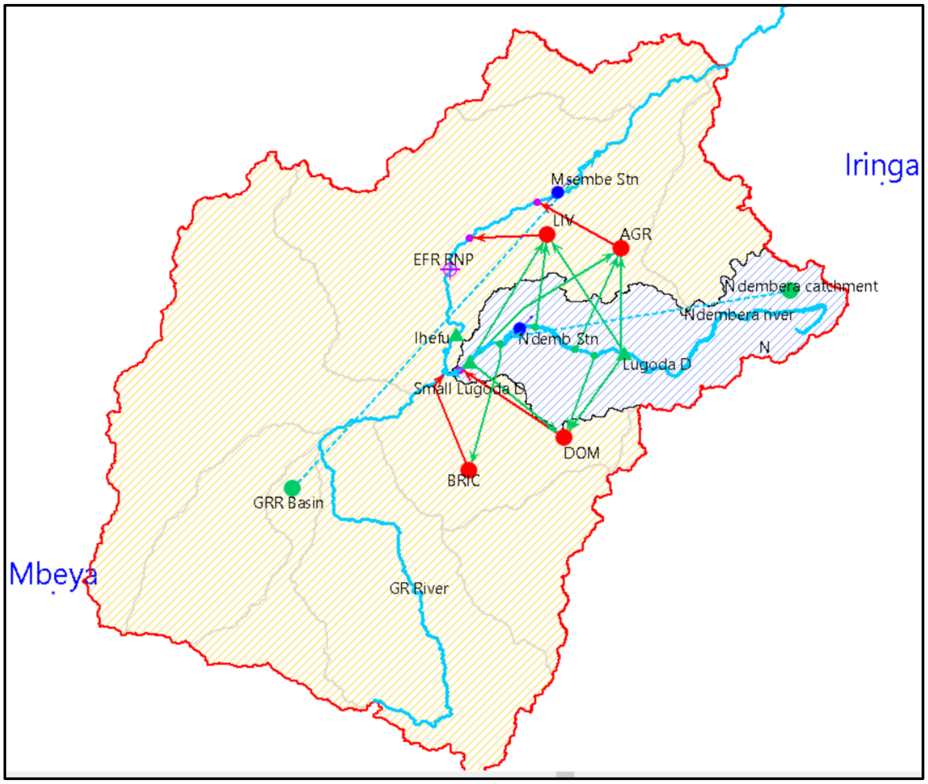


Figure 3.12: WEAP Schematic View of Demand sites in GRR catchment

Annual Activity Levels

In WEAP, the annual amount of water required by each demand is represented in the annual activity levels. Calculation of consumed water in each demand site is done by multiplying the overall levels of activity and the water use rate based on the monthly variation of each demand.

Annual Water Use Rate

The water use rate has been used as the average annual water consumption per unit activity. The annual water use rate is displayed in the denominator to show that it was a rate per unit, not the total amount of water used. The study calculated the annual water use rate per person and per hectare and then converted to m³/annum and provided as input to the WEAP system.

Monthly Variation

The monthly analysis from the first month of the current account year through the last month of the last year was performed by WEAP system. The current account year is defined as the most recent year for which reasonably reliable and complete data is available and from which future demand projections can be made (Droogers, 2009). Monthly variation was important and it was based on the monthly requirement of each demand sites. Whenever demand was considered constant throughout the year, monthly variation column was left blank. A twelve-monthly coefficient was summed to 100 percent. Whenever demand did not vary, all months were assumed to use the same amount, according to the number of days in the month.

3.7 Input Data Preparation for WEAP Model

3.7.1 Population Projection

In this study, two methods were applied to estimate the population growth of the study area: the arithmetic method and expression builder methods. Since the available data of population found in the GRR basin is from the population census report of 2013, the arithmetic growth method was used to project the 2012 data so as to get the current population (2018). This method is commonly used for population projection in water design projects or water development programs in Tanzania. The equation for the arithmetic growth method is given below.

$P_n = P_0(1 + R)^{T_n - T_0}$……………. (3.1)

Whereby

P_n = Projected population in number

P_0 = Baseline population in number

R = growth rate in percentage

T_n = Projected year

T_0 = Baseline year

The WEAP model is built with Expression Builder function as “GrowthForm” which used to project the population of the reference period (2019-2050). The purpose of this tool is to build the WEAP expressions by dragging and dropping the functions and the WEAP branches into an editing box.

The input data in Growth Form field within WEAP for projecting the population for the reference period is the:

- Year of last census 2012
- Population in 2012= 32693
- Per capital water use = 60lcap/day (rural areas)
- Normal population growth rate for Mbarali is estimated to be 2.2%
- Estimated high growth rates for Mbarali districts is 2.8% (i.e. for the year 2018 – 2050)

3.7.2 Irrigation Water Demand

Irrigation activities are one of the sectors which use water in this catchment. Thus, the irrigation water demand was found to be one of the key assumptions in scenarios development when evaluating the impact of water use in the study area. It is well known that the irrigation water demand differs depending on the type of crops grown and the evapotranspiration. Because paddy is the dominant crop grown in the basin, it was chosen to represent other crops grown in the basin. Accordingly, the water demand for irrigation differs from one climatic season (dry or wet season) to another. Hence, the monthly variation in water consumption was also considered as the main factor. Paddy is cultivated for seven months from early December to May (Mdemu & Francis, 2016) and some places dry season irrigation is taken from August to November (Kadigi, 2003).

Table 3.4: Monthly share of annual irrigation water requirement for Madibira farm used in the WEAP model.

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
Percentage	16.2	16.2	16.2	16.2	13.1	1.9	1.9	1.9	1.9	1.9	6.3	6.3
Flow rate (m^3/s)	4.3	4.3	4.3	4.3	3.5	0.5	0.5	0.5	0.5	0.5	1.7	1.7

The total irrigable land in this case study is 4000 ha. A reference scenario is established to evaluate the impact of the possible future irrigation development in the catchment in consideration of water balance. In this case, the scenarios were built based on the assumption that the irrigable lands are within the areas where access of water from the river or dam will be by gravity (e.g., diversion by pipes or channels). The annual water consumption per hectare was adopted from the average water consumption for paddy production in Usangu plain (13600 m^3 /ha). This water consumption per hectare includes all losses, percolation, and absorption (Kadigi, 2003).

3.7.3 Estimation of Livestock Water Demands

The total annual water demand for livestock in Ndembera catchment was estimated to be 0.045Mm^3. The assumption was made that this water demand will be acceptable for a long time due to a plan of having a controlled livestock population in the basin. Based on the study conducted by SMUWC, (2001) the water demand per head per day for the cattle, donkeys, sheep and goats, which are found in the basin are shown in Table 3.5. Livestock water demands are based on livestock census and population density of the livestock in the basin. Thus, water demands can then be estimated from consumption rates.

Table 3.5: Livestock water requirement in Ndembera catchment

Stock Type	**Unit Demand (l/head/day)**	**Approximately population**	**Annual Water demand (Million m3)**
Cattle	30	5000	0.041
Sheep and Goats	3	3250	0.003
Donkeys	35	150	0.001
		TOTAL	**0.045**

3.7.4

Environmental flow demand

In some demand sites, such as environmental flow requirement in the RNP where water use may remain constant throughout a year, while other demands may vary considerably from month to month. Due to variation in climatic season, the demand in water for environmental flow varies as well. This is influenced by the high demand for limited water resources from the river by different sectors, hence leading to a reduction of the flow of the river downstream.

Table 3.6: Monthly Environmental Flow Requirement (EFR) for RNP

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
EFR (m^3/s)	4	4	4	4	4	7	7	7	10	10	10	7

3.7.5 River Flow

The management of the river and water allocation practices were simulated using historical naturalized streamflow to represent the basin hydrology (Yaqob et al., 2015). The historical daily streamflow data (1971-2018) of Ndembera (1KA15 at Ilongo) and GRR (1KA59 at Msembe ferry) was obtained from RBWO. The data from 1971 to 1990 were aggregated to get historical monthly flow, as shown in Table 3.3 as well as the gauging station is shown in Figure 3.7. Accordingly, the data for Lugoda dam was obtained from WWF (2010) report.

Table 3.7: Average monthly discharge for Ndembera river and Great Ruaha River

River	**Monthly**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ndembera river (m^3/s)	8.4	13.6	17.3	24.5	18.1	8.8	3.7	3.0	1.9	1.3	1.6	3.3
GRR Flow (m^3/s)	85.6	212.1	233.5	222.8	133.8	57.3	16.8	3.3	0.8	0.3	0.6	9.9

3.8 Water allocation priorities

WEAP system uses a linear programming technique in performing water allocation model.

The classification of water demand and allocation priorities range between 1 to 99. The highest priority is denoted by 1, while 99 is the least priority in water demand allocation. A demand priority and preference driven approach is used to present a robust solution algorithm to solve the water allocation challenges.

A standard linear program is used to solve the water allocation problem whose objective is to maximize the satisfaction of demand, subject to supply priorities, demand site preferences, mass balances, and other constraints. Two user-defined priority systems applied for determining allocations from supplies to demand sites:

Demand Priorities and Supply Preferences.

i. Demand Priority

This is used to determine the demand site's priority for supply. Demand sites with higher priorities are processed first by the WEAP Allocation Algorithm. Reservoir priorities default to 99, meaning that they would fill only if water remains after satisfying all other demands. Many demand sites can share the same priority. Accordingly, if priorities are the same, shortages will be shared equally (Arranz & McCartney, 2007). These priorities are suitable in representing a system of water rights and are also crucial during a water shortage (SEI, 2015).

ii. Supply Preferences

This is used to indicate the preferred supply source where there is more than one source to a demand site. Using the demand priorities and supply preferences, WEAP determined the allocation order to follow when allocating the water.

In the Great Ruaha River Basin, the following priorities were set during scenarios analysis:

(i) Domestic Water Demand = 1;
(ii) Environmental flow requirement = 2
(iii) Agriculture Water Demand= 4
(iv) Pastoralism water demand = 5
(v) Bricks making water demand = 3
(vi) Others (filling reservoirs and others) = 99.

The study assumed that the livestock sector also has alternative water sources like ponds and boreholes and therefore withdrawal from the dam is given a supply priority value of 5. Also, Madibira irrigation scheme is assigned a supply priority of 4. This is because other alternative sources such as runoff of the river and ponds are also used. These priorities were adopted in order WEAP to understand which demand sector should be given the first, second, third, and the last one.

Scenario Analysis

In this study, a reference (business-as-usual) scenario was used to incorporate currently identifiable trends in development, water supply availability, water-use efficiency, and other aspects. Current water accounts and the reference scenarios are outlined based on the continuation of existing patterns.

This study involved the following scenarios: Reference scenario or Business-as-usual scenario, the scenario for water demands and water allocation. Based on Reference scenarios, the following was further developed and can be understood from the following 'what if' pre-supposed situational queries:

Reference Scenario:

Ref, coded as "Reference" at 2.2% Madibira population growth rate Business-as-usual, outlined based on the continuation of current patterns.

i. Scenario 1: Increase in Population Growth Rate

This involved the assumption after the construction of the dam that the water availability and power supply will attract people to the catchment. So, what if there would be high population growth which will influence the increase in domestic water demand was considered. The scenario was estimated to change demand from a level of 2.2% - 2.8% in 2019-2050 (NBS, 2013).

ii. **Scenario II: Moderated Population Growth Controlled with Integrated Supply & Demand Measures at 2.2% growth rate.**

What if there would be normal population growth but with integrated measures and controls of demand and supply such as the improvement of abstraction and storages along the Ndembera river, GRR, and demand controls such as water-saving initiatives and reduction of unaccounted-for water. This Scenario was estimated to change demand at the level of 2.2% (2019-2050)

iii. **Scenario III: Construction of Lugoda dam** (350MCM) which it has to be used as a primary source of water supply to the demand sites.

iv. **Scenario IV: Application of environmental flow requirement (EFR) in the RNP** In the scenario, the monthly variation in water demand was considered during the simulation, as shown in Table 3.6.

v. **Scenario V: Increase the water storage capacity of Ihefu swamp.**

Ihefu swamp is considered on the source of water loss in the basin. This is due to its large surface area and shallow which influence high evaporation during the dry season. In this study, it was assumed that the increase in swamp storage capacity (i.e. construction of 1m water sill weirs) will help to regulate the flow of the river downstream (RNP) during the dry period.

vi. **Scenario VI: Construction of series of reservoirs in Ndembera and GRR (in RNP) river.**

This scenario was intended to increase water harvesting and during wet season where the floods occur and release the water during the dry period.

vii. **Improvement of agricultural water abstraction infrastructure and irrigation systems.**

While it has been mainstreamed over the last decade to take action on improving the irrigation strategies in the GRR basin, the study indicated an unsatisfactory utilization of water use permits unclear types or methods of irrigation and water use that are permitted beyond a distinction of either irrigation or domestic water use. Currently, the traditional furrow and flood techniques are widely used in paddy irrigation in the basin. These methods indicated a low level of irrigation efficiencies and employed surface-based irrigation water distribution systems using canals (bunds) often built of soil. The observed short canals built of heavy soils leads to higher irrigation, while longer channels lead to lower efficiencies. In this regard, it has been found that the effectiveness of these unlined, soil only, systems range from 36% to 54% (McClain, Kashaigili, & Ndomba, 2013). The absence of irrigation gates, poor maintenance of irrigation components leaking, excessive flooding, and very little return flow has been found to contribute to additional water loss up to 50% of the value presented above.

Evaporation from the surface of the water, percolation of water deep into the soil resulted from standing water were found to be among the factors exacerbating the water loss in irrigation sectors. The weeds growing in some of the canals leads into obstruction of water flow and aggravating the water loss through transpiration. According to McClain, Kashaigili, & Ndomba (2013), the poor operation and maintenance of irrigation infrastructures in Tanzania (the lack of return flow in water diversion systems, improper flow control and other problems) cause existing irrigation infrastructures to be inefficient. These weaknesses lead to very low efficiencies in the range of 15% to 20%.

Moreover, the study revealed that actual irrigation abstractions from the river system are based on the capacity of the intake structure (Table 3.8) rather than on the crop water requirements. When water available in the river is less than the design capacity of intake, then whatever water is available in the stream is diverted. This case has found that about 90% of the river flow has been diverted to irrigation schemes.

Table 3.8: Summary of Total Abstraction from Great Ruaha Sub-basin Rivers (Source: Machibya, 2005)

Sub-catchment	**Mean Flow (cumecs)**	**Total Maximum Abstraction (cumecs)**	**Number of off-takes**	**Level of Abstraction (%)**
Ndembera	15.13	4.3	6	65

Kyoga	13.84	7	11	100
Mbarali	15.6	8.5	3	100
Mlomboji	2.65	0.1	1	50
Kimani	6.58	4	5	95
Ruaha	19.24	5	1	85
Chimala	4.87	2.8	7	100
Mkoji	10.62	12	70	100
Mjenje	18.18	0.6	12	70
Kimbi	15.81	0.2	3	70
Northeast	2.24	0	0	0

viii. Expansion of irrigable land by 50% and 100%

This involved Normal Growth Irrigated Acre Expansion of 50% (Phase I). What if there would be an expansion of irrigated Agricultural Acreage by 100% during the wet season as planned by Madibira Agricultural Marketing Cooperative Society after the construction of the Lugoda dam. The Key Assumptions developed were: (a) Monthly Variation (which included Domestic, Agricultural aspects and (b) Drivers (which included Population Growth Rate, Technical Innovation, and Efficiency Improvement).

3.9 Model Calibration and Validation

Calibration is defined as the iterative adjustment of model parameters such as roughness, hydraulic structures coefficients, etc. so that the model reproduces the observed prototype data at an acceptable accuracy (Brunner, 2008). According to SEI (2015), calibration is the alteration of some parameters (model constraints) to simulate better historical patterns such that to get a good match between simulated and observed data at a selected node. Thus, in order to get a reliable value of some parameters, the calibration of the model is vital to be performed (Droogers et al., 2014).

In WEAP21, the calibrations ensure the linkage to parameter estimation tool (PEST) that allows the user to automate the process of comparing WEAP output to historical observations and modifying the model parameters to improve its accuracy (WEAP, 2014). In order to have proper calibration, the data to be used should have a sufficient range of hydrological events to activate all model constituent processes during calibration. This will require at least ten years of continuous data, which involves average dry and wet years (Okungu, 2018). According to Okungu (2018), WEAP21 has no routine for automatic calibration; hence, a manual approach was applied to compare the simulated and the observed time series.

The calibration and the validation were performed using hydrologic datasets of observed stream-flows at the gauging station in GRR (Msembe station) and Ndembera River (Ilongo station). The historical dataset for the period 1990 – 2005 was used for calibration, and a subsequent set for validation period 2006-2015 were used. The 1990 – 2005 period was considered suitable as they had small missing values in daily-observed streamflow data. The model was run on a monthly timestep, and relative water availability was tracked based on water balance dynamics (climatic data). Calibration was performed in WEAP by a trial-and-error method to maximize the correlation coefficient (R) so as to determine the ability of the data to reproduce the actual average monthly flow volume.

The initial estimates of calibration coefficients were done, and parameter adjustments performed appropriately to improve the R and Index of Agreement (IA) values. The model was then used to forecast demand for a suggested period (2019-2050). Three fitness criteria were used for model comparison: Efficiency (Nash-Sutcliffe coefficient), Correlation factor, and Index of Agreement.

Statistical Computations

The comparison of the results of hydrological model performance was made using various statistical parameters, which included the observed and simulated flows, mean flows, coefficient of determination, index of agreement, and correlation. This analysis involved the Nash-Sutcliffe Coefficient (R) and Index of Agreement (IA), which are common parameters to evaluate the goodness-of-fit measure of the performance of hydrological models.

The following are mathematical expression to compute the parameters listed above.

$$IA = 1.0 - \left(\frac{\sum_{i=1}^{N} (Q_{oi} - Q_{av})^2}{\sum_{i=1}^{N} \left\langle |Q_{si} - Q_{av}| - |Q_{oi} - Q_{av}| \right\rangle^2} \right)$$ Index of Agreement (IA)……... (1)

$$E = 1.0 - \left(\frac{\sum_{i=1}^{N} (Q_{oi} - Q_{av})^2}{\sum_{i=1}^{N} (Q_{oi} - Q_{av})^2} \right)$$ Nash-Sutcliffe Coefficient(R)…………...…... (2)

Where:

Q_{oi} is the observed streamflow at time (m^3/s)

Q_{si} is the simulated streamflow at time (m^3/s)

Q_{av} is the average streamflow (m^3/s)

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

3.10 Reservoir Operation Rules

Generally, the main purpose of the reservoir is to provide a source of water for demand sites during dry periods. WEAP can simulate a reservoir taking account the reservoir's operating rules, downstream requirement priorities, net evaporation on the reservoir, and hydropower generation.

The reservoirs can use a zone-based operation and this reservoir storage is divided into four main zones (Figure 3.9):

1. Flood-control zone (Sf) that can hold water temporarily; therefore, release can be controlled.
2. Conservation zone (Sc) which is available storage for downstream demands
3. Buffer zone (Sb) that can be used to control and regulate water demands during dry periods
4. Inactive zone (Si) which is dead storage

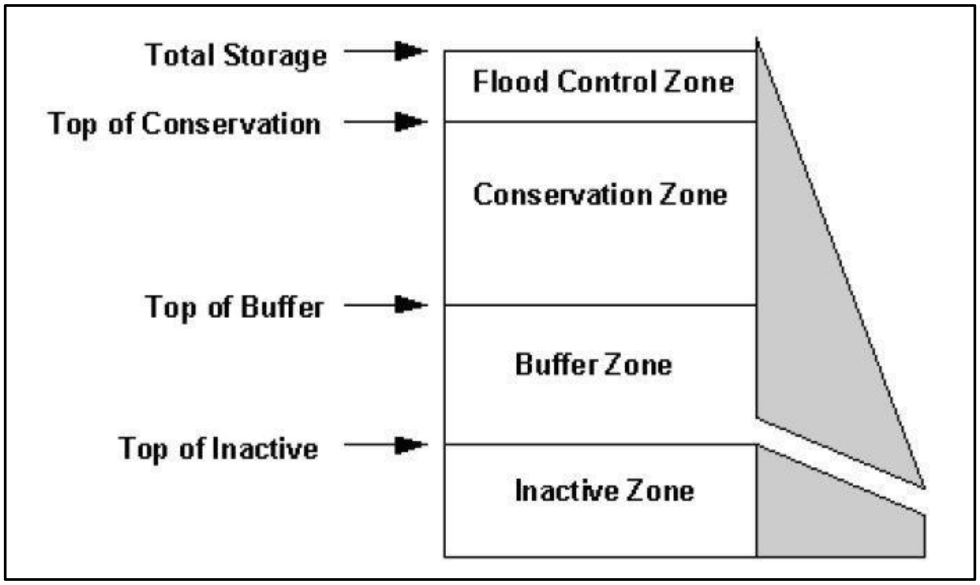


Figure 3.13: Reservoir storage zones (Source: WEAP User Manual)

The total amount of available water for release from a reservoir is the summation of the storage in the flood control zone, the conservation zone, and a fraction (given by bc) of the storage in the buffer zone.

$$Sr = \mathrm{Sf} + \mathrm{Sc} + (bc * Sb) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

Where Sr is total available water that can be released from the reservoir, Sf is the storage of flood control, Sc is the storage of conservation, and bc is the buffering coefficient.

Ndembera reservoir was considered under the reference scenario to evaluate the effects of the application of operation rules on supplies to water users. The determination of how much water is available in the current time step to be released for downstream demands and EFR is considered in the operation criteria of the reservoir (Richter & Thomas, 2007). The WEAP model will allow for a release of only as much of the available storage as is needed to satisfy the demand and the EFRs while taking into consideration releases from the rivers or other sources.

In this study, the reservoir's set to a priority level of 99. The priority of 99 (the lowest possible priority value) means that the reservoirs will fill only after all other demands have been satisfied. The application of reservoir operation rules affects water supply to downstream users.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

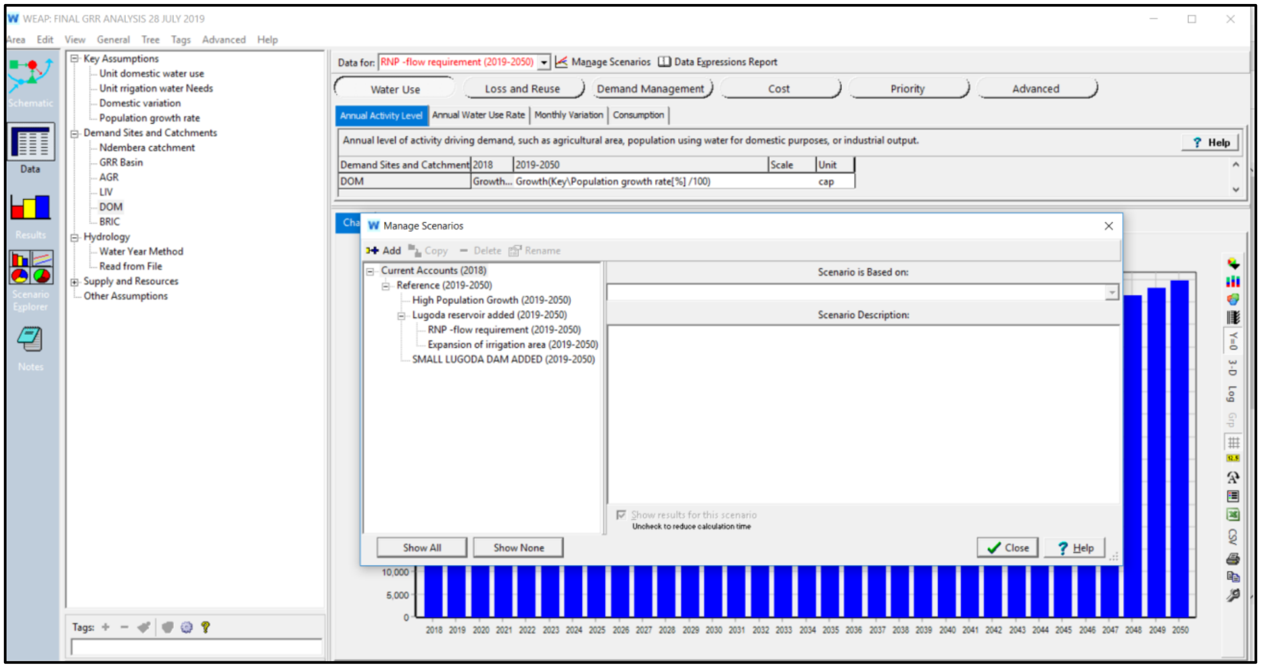
The main strategic areas of the study included managing the risks of droughts, floods, and impacts of climate change through mixing the structural and non-structural measures as well as protecting and conserving the diverse habitats and ecosystems.

It was also considered necessary to consolidate water governance in order to enhance institutional coordination and stakeholder participation so as to ensure equitable allocation and efficient use of water resources.

Other strategic areas of the study were the development of and improvement of water supply and sanitation services so as to provide for the social needs of the basin population. This aimed at increasing safe water and improving sanitation coverage in rural areas by developing water resources and construction of sanitation facilities in rural areas found within the basin as per national targets. Moreover, the restoration of the river is expected to support multiple economic activities, thereby contributing to increase household income, food security, energy security as well as employment opportunities.

The results of the ecological flow in RNP and the water supply for other sectors depending on the GRR and Ndembera river are presented in this chapter. Previously, the two scenarios for options for restoring the GRR defined by SMUWC (2001) were described. For this study, five scenarios have been analyzed that are based on the reference scenarios.

The WEAP model was set up for water demands and supply with the baseline year of 2018 and was run up to 2050. The scenario analysis approach was used to assess the Ndembera river and GRR Basin water balance, its water allocation situation for the projected period from 2018 up to 2050 and possible option for supplying ecological water demand to RNP and other sectors. The analysis was based on five main scenarios (Figure 4.14). Under each scenario, the projected water demand was computed and the demand coverage or unmet demands were analyzed. The impact of these scenarios has been analyzed by using the WEAP model. Moreover, the study evaluated the option suitable for restoring the dry season flow of the GRR to sustain the ecological water supply to RNP.



Data for: RNP -flow requirement (2019-2050)

Annual level of activity driving demand, such as agricultural area, population using water for domestic purposes, or industrial output.

Demand Sites and Catchment	2018	2019-2050	Scale	Unit
DOM	Growth...	Growth(Key\Population growth rate[%] /100)		cap

Figure 4.14: Scenario development within the WEAP model

4.2 Calibration and Validation

In this section, simulated results have been compared for naturalized flows at each control (gauging) station (Msembe and Ndembera at Ilongo). Comparison of observed values (taking account of statistical parameters of data from the two (2) stations located within the basin) was made against results of the WEAP model. Results indicate that WEAP is capable of producing hydrological dynamics of the GRR Basin as illustrated under calibration and validation processes below.

Monthly simulated and observed streamflow data for the calibration period (1990 - 2015) can be seen in Figure 4.15 & 4.16 for the control stations (Msembe and Ilongo).

4.2.1 CALIBRATION

Relationships between monthly simulated and observed flows indicate significant correlations whose coefficients vary from 0.63 to 0.95 (Table 4.9). These statistical results imply good model performance in reproducing streamflow trends. This could be influenced by the topography in the middle and upper basin (high slope), the size of the catchments, and other factors.

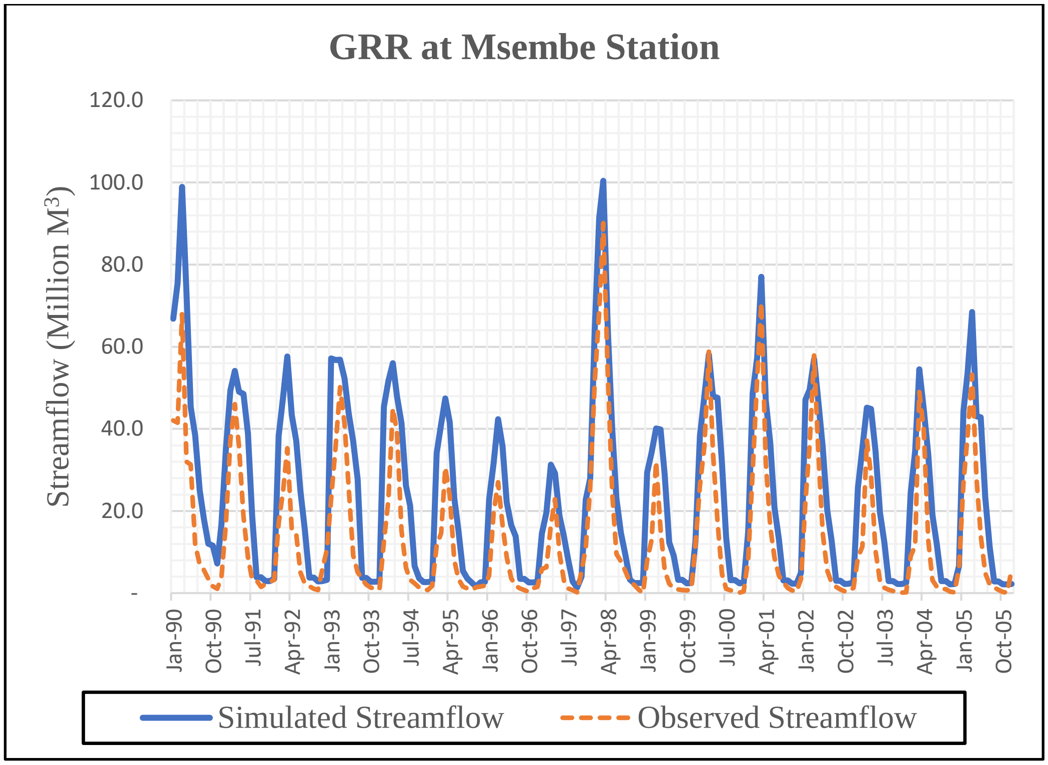


Figure 4.15: Calibrated flow for GR River (Msembe station 1KA59)

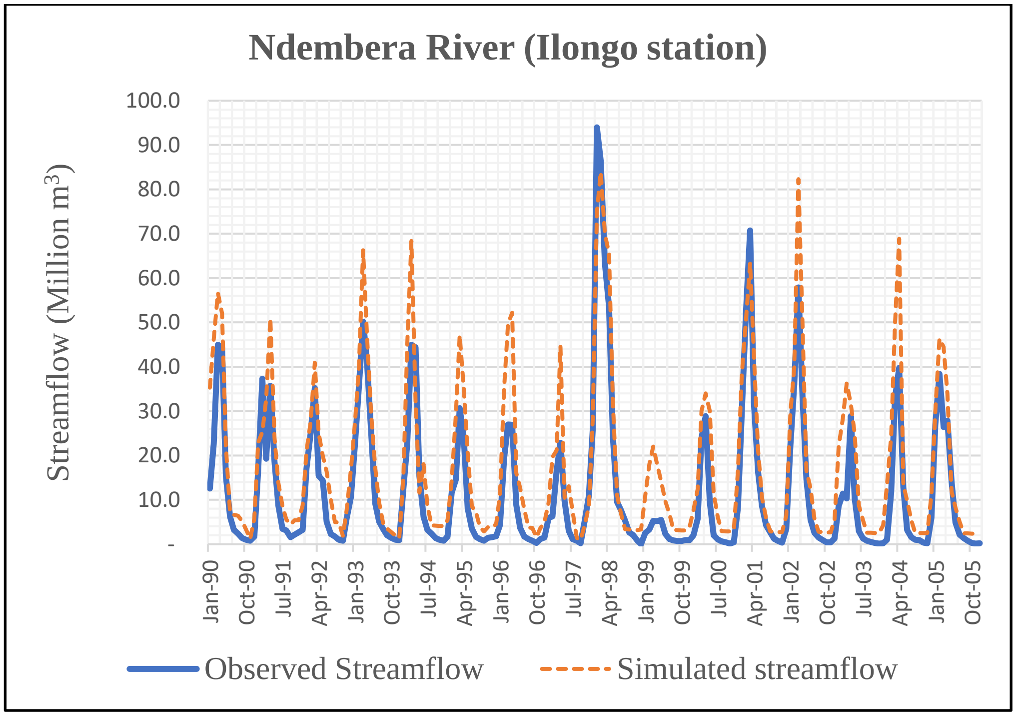


Figure 4.16: Calibrated flow for Ndembera River (Ilongo station 1KA15)

Summary of Annual and Monthly Fit Statistics for calibration data is provided in Table 4.9 as observed by WEAP and Observed Stream Flows at 2-gauge stations in the GR River Basin, from January 1990 through December 2005 of the calibration period.

Table 4.9: Fit Statistics of Simulated and Observed Stream Flow data for calibration

Fit Statistic	**GRR at Msembe Station.**	**Ndembera River at Ilongo Station.**
Nash-Sutcliffe Coefficient (E)	0.95	0.83
Index of Agreement (IA)	0.983	0.86
Coefficient of Determination (r2)	0.88	0.77
Coefficient of Correlation (r)	0.94	0.88

4.2.2 Validation

In order to validate the calibrated hydrological model, data was entered and run for a time period (2006- 2015) to model performance because the calibration had been performed under normal hydrologic conditions. Results of the model validation are presented in Figure 17 and 18. For the two selected stations, simulated monthly flows were observed to be close to naturalized flows.

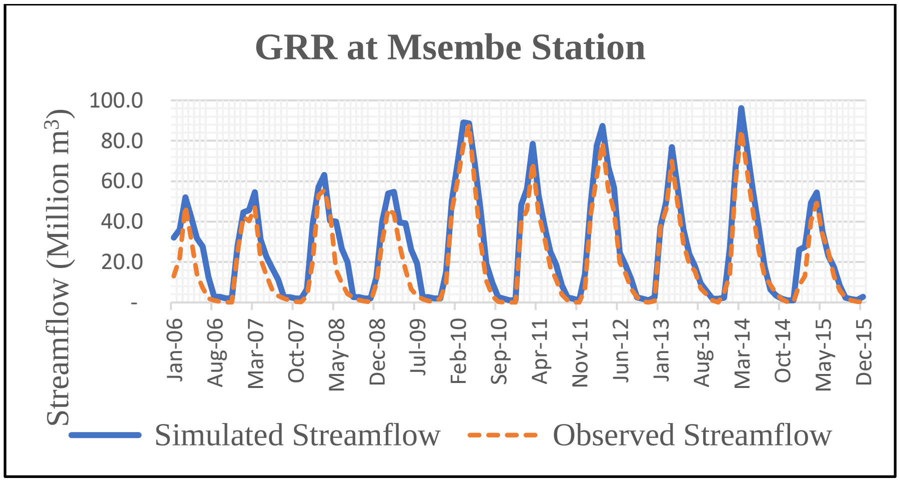


Figure 4.17: Validated flow for Great Ruaha River (Msembe station 1KA59)

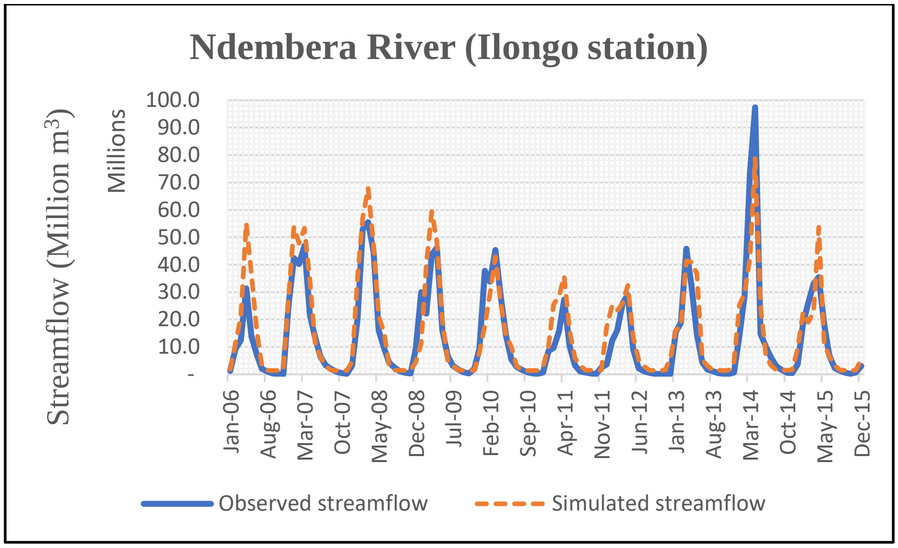


Figure 4.18: Validated flow for the Great Ruaha River (Ilongo station 1KA15)

Summary of Annual and Monthly Fit Statistics for Simulated validation data by WEAP and Observed Stream Flow data at two gauging stations in the GRR Basin is presented in Table 4.10 for January 2006 through to 2015 of validation Period.

Table 4.10: Fit Statistics of Simulated and Observed Stream Flow data for validation

Fit Statistic	**GRR at Msembe Station.**	**Ndembera River at Ilongo Station.**
Nash-Sutcliffe Coefficient (E)	0.86	0.78
Index of Agreement (IA)	0.92	0.82
Coefficient of Determination (r2)	0.88	0.74
Coefficient of Correlation (r)	0.94	0.86

For calibration and validation process, the larger values of Index of agreement, Nash-Sutcliffe Coefficient (E), Coefficient of Determination (r2), and Correlation Coefficient (r) demonstrate small differences between simulated and observed values of streamflow data. Therefore, the model's statistical calibration and validation results show satisfactory performance in reproducing the outputs needed for analyzing the results of the scenario.

4.3 Reference Scenario

Net evaporation from reservoirs was specified in WEAP by computing the difference between monthly potential evaporation and precipitation. Time series of rainfall was derived from the "rainfall zone" in which each of the reservoirs was located. The water temperature of the Ndembera River and GRR was specified in the WEAP to simulate the water balance of the river and reservoirs.

Evapotranspiration of the Ihefu swamp which has been considered as a reservoir for regulating the flow of the river during the dry period. This helped to simulate the water balance of the swamp (Figure 4.19). Moreover, the monthly average GRR flow was defined to which indicated high seasonal flow variation. A high flow of the river was found to begin in February and ends in June in which April was found to be the peak flow of the year. The dry period of the river starts in July to December in which minimum water flow of the river was found to occur from September to October.

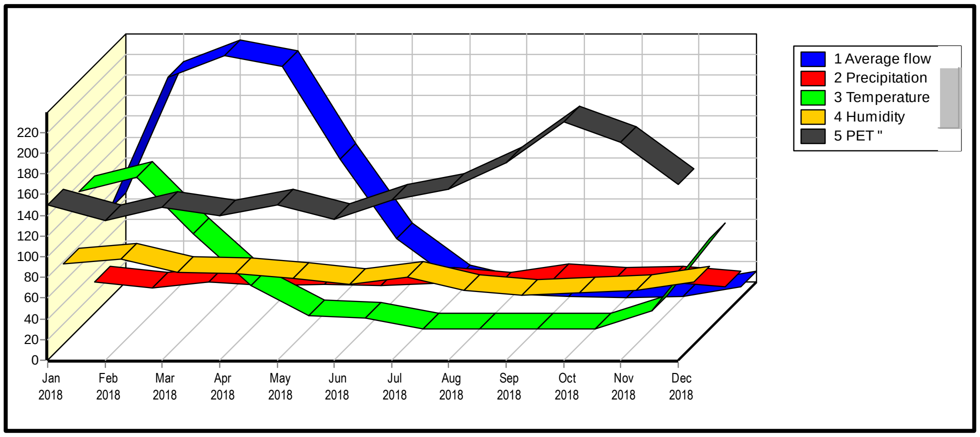


Figure 4.19: Average monthly GRR flow, precipitation, temperature, humidity, and potential evapotranspiration of the catchment.

4.3.1 Future Water Demand at Current Accounts

The water demand in the catchment differs significantly from one sector to another. Agriculture is the sector which was found consume a lot of water from the catchment followed by domestic use, livestock watering and bricks making being the least water consumer. For agriculture, the water demand was found to vary significantly during the wet season and dry season. During the wet season a whole irrigable land is being irrigated for paddy production in which the highest average monthly water demand was found to be 5378.40 thousand cubic meters (TCM) (January to March) while the lowest was found to be 630.8 TCM (June to October) where part of the irrigable land is being irrigated for summer plantation of paddy.

Domestic water demand was found to have a slightly monthly water demand variation (averagely 57.61 to 63.24 TCM per month). This has been attributed to the fact that during the wet season some people tend to harvest rainwater for their domestic uses while during the dry period they entirely rely on the river as a source of water supply. Livestock and brick making water demand were found to be in more demand during the dry period of the year whereby livestock water demand ranges between 12 to 24 TCM while bricks require a monthly average of between 0.4 to 1.5 TCM in June to October (Figure 4.20).

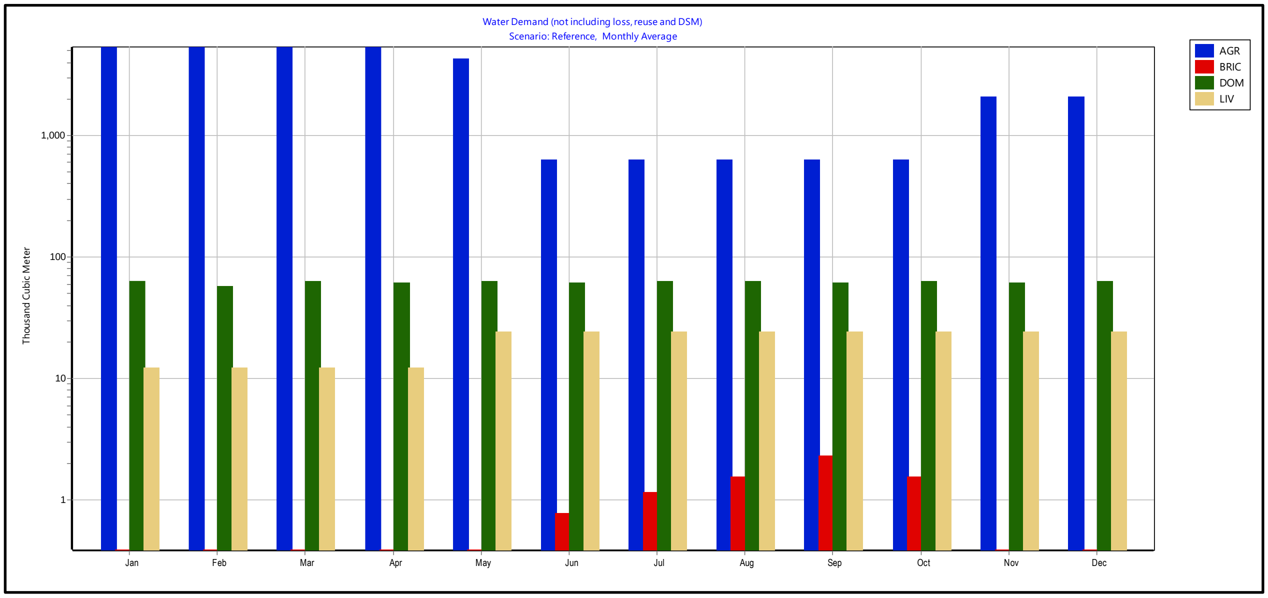


Figure 4.20: Average Monthly Water Demand Per Sector in TCM

Of the total annual river flow in GR Basin across all gauging stations, 6.2% was simulated as evaporation, while 4.7% was an estimate of surface water inflow. Majority of the streamflow occurred during the wet months (January to June at 80.1%, while the dry months (July to December) only contributed to 19.9% of the river flow (Figure 4.21).

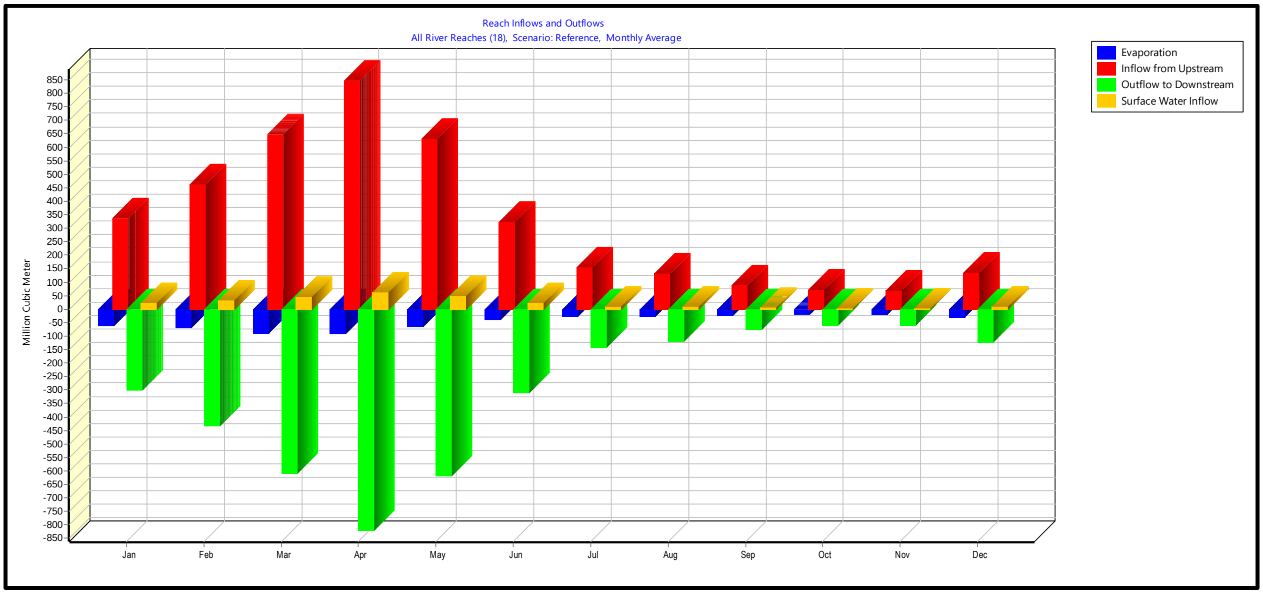


Figure 4.21: Reach inflows and outflows within GRR Basin

4.3.2 Water supply from Ndembera River and GRR to demand sectors

The water flow in the river is insufficient to supply to all the demand sites throughout a year. The unmet demand has been revealed to occur in agricultural, domestic, and livestock watering sector with a deficit of 640, 23.17, and 10.45 TCM respectively. Note that, because all the demand sites were assigned the same supply preference of 1 when water shortage occurred in November, all demand sites faced a shortage of water except bricks making sector which had minimal water demand compared to the rest. In November the unmet demand for agriculture was found to be high because this is the month were farmers need much water for preparing their farms' irrigation while the river still has small flow. Figure 4.22 shows that all months except November have registered 100% water supply coverage from the river for these four sectors.

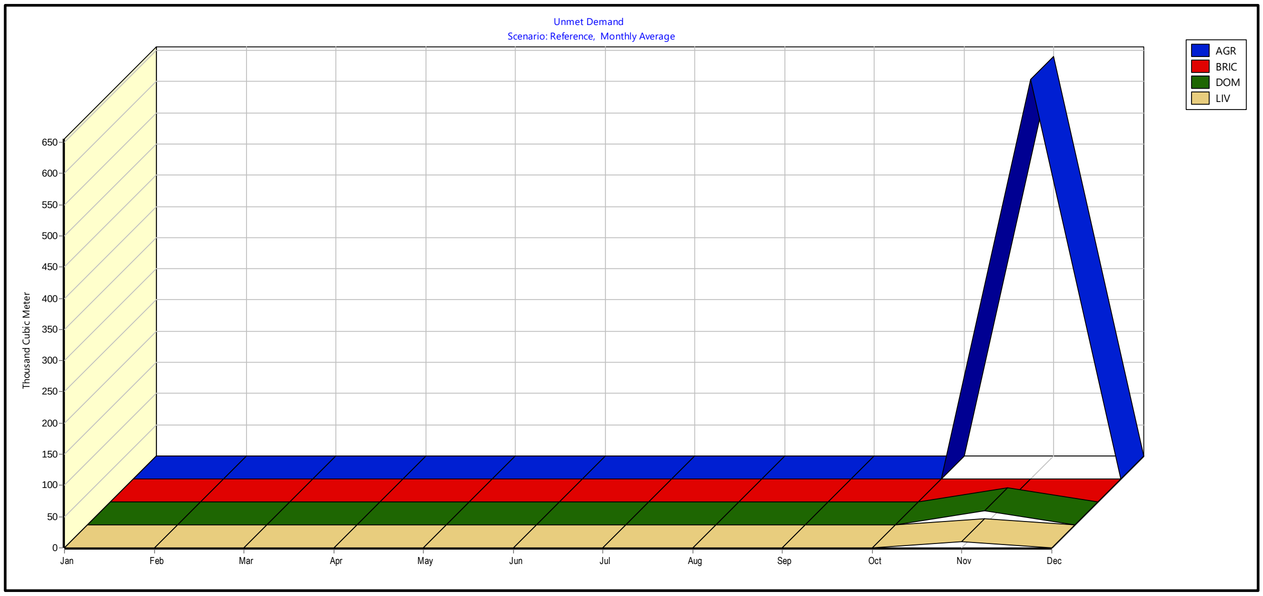


Figure 4.22: Monthly average Unmet demands under the reference scenario

4.3.3 Demand Site Coverage (% of requirement met) monthly domestic variation assumption

Application of domestic variation scenario in has shown that the domestic water coverage has changed from 23.17 TCM to full coverage. Thus, domestic has no longer unmet demand in November because the fraction of demand in November decreased from 8.5% (originally based on the number of days in the month) to 7.5% (now based on the expression using domestic key assumption).

In this scenario, it has been shown that the domestic and brick-making sectors water demand will be met for 100% throughout a year. This is contrary to the agricultural sector where the demand coverage drops from 100% in September to 69.1% in October. The livestock water demand coverage dropped from 100% in September to 59%, in October (Figure 4.23).

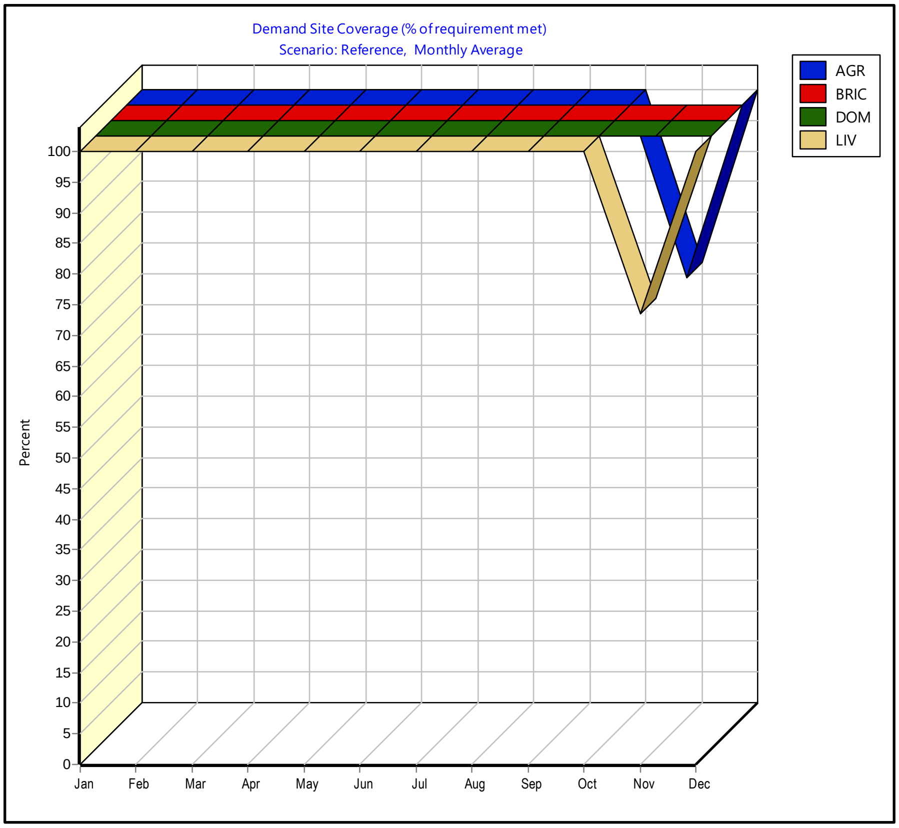


Figure 4.23: Average monthly Demand Site Coverage under domestic variation assumption

4.3.4 Population growth under normal growth rate of 2.2%

The normal population growth rate of Madibira ward found in Ndembera catchment is 2.2%. The WEAP system was run to project the population size in different years of the project design period (2018 to 2050). Figure 4.24 indicates the expected number of people per each year. These numbers are important as they helped to analyze the water demand and supply required for a specific period of the project. In this case, the study showed that by 2050, the population of the catchment will almost be doubled, which indicate high domestic water demand will be expected.

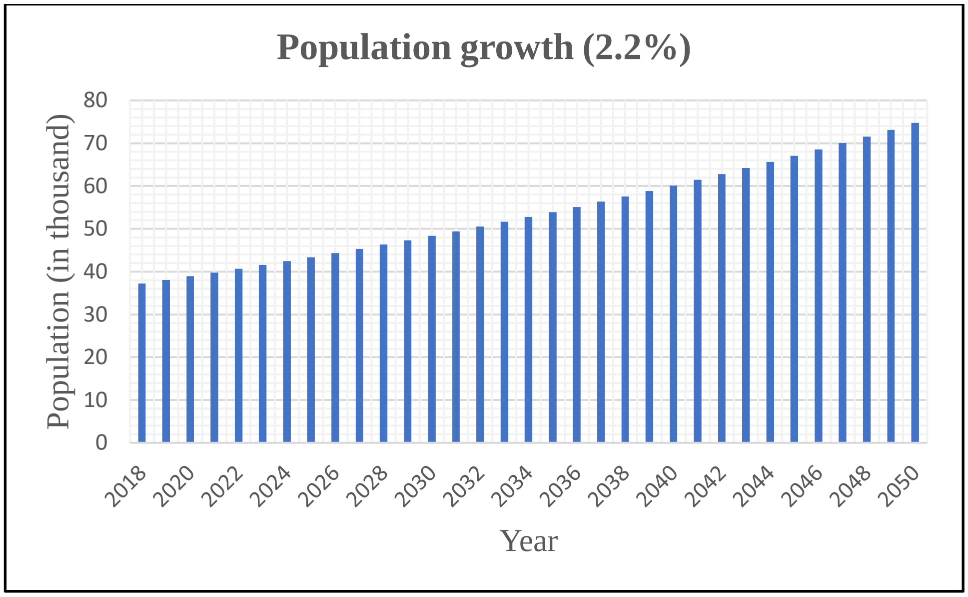


Figure 4.24: Forecasted normal population growth in the Ndembera catchment

4.4 Scenarios Analysis

4.4.1 Irrigation system improvement scenario (technology and abstraction infrastructures improvement)

Considering the high amount of water loss occurring in the irrigation sector, there is a need for improving the management of the water abstracted from the river to farms. This improvement includes water abstraction infrastructures, irrigation, and plantation methods. One of the most important practices that can be adopted is to line the primary and secondary canals with concrete. Lining the surface of water irrigation canals increases the efficiency of distribution of water by reducing the potential of siltation of channels and opportunities for weeds to obstruct water flow. The introduction of return flow has also shown the reduction of water demand in the sites.

However, considering the fact that lining the canals does not influence the efficiency of utilization of water when it reaches the fields, other options suitable for insuring efficiently management and use of water are adopted. Among those options are: utilize metering devices and pay-per-use to discourage over-watering; grade land slope for best soil wetting with minimal erosion and runoff; channel excess water to return to the source to reduce standing water evaporation; provide accurate weather forecasts to help improve irrigation timing and amounts.

Encouraging a randomized water allocation method for smallholders to minimize the risk of tail-end fields being allocated water ‘out-of-season’ need to be promoted.

There is a need to encourage the transplanting of rice (vs direct seeding) to minimize seasonal water use, adoption of short-season rice varieties to reduce seasonal water use. Additionally, demonstrate to farmers proper furrow depth and width for optimal soil wetting, size gates, spills, bund cuts to ensure an appropriate soil wetting across field width for furrow irrigation systems, and install effective gates that provide proper ‘head’ for spills or siphon tubes.

4.4.1.1 Annual Total Water Demand (not including loss, reuse, and DSM)

The study found that the improvement of the irrigation systems will result in a gradual decrease in water demand for the agricultural sector. The total annual water demand for agriculture decreased from 33.2MCM currently abstracted (2018) to 22MCM (2050) which means 33.7% of water abstracted will be saved. The saved water (11.2MCM) will help to supply to other demand sectors downstream of the catchment. The normal population growth is expected to result in a linear increase in the total annual domestic water demand from 0.75MCM (2018) to 1.49MCM (2050) which is almost 50% increase in water demand. The study considered that the livestock keeping and brick-making sectors will be controlled so as to avoid the water demand increase. This will be implemented by controlling the number of animals to be owned or kept in the basin and efficient utilization of water abstracted for brick making industries. For that case, the study found no increase in water demand for the entire simulated period (Figure 4.25).

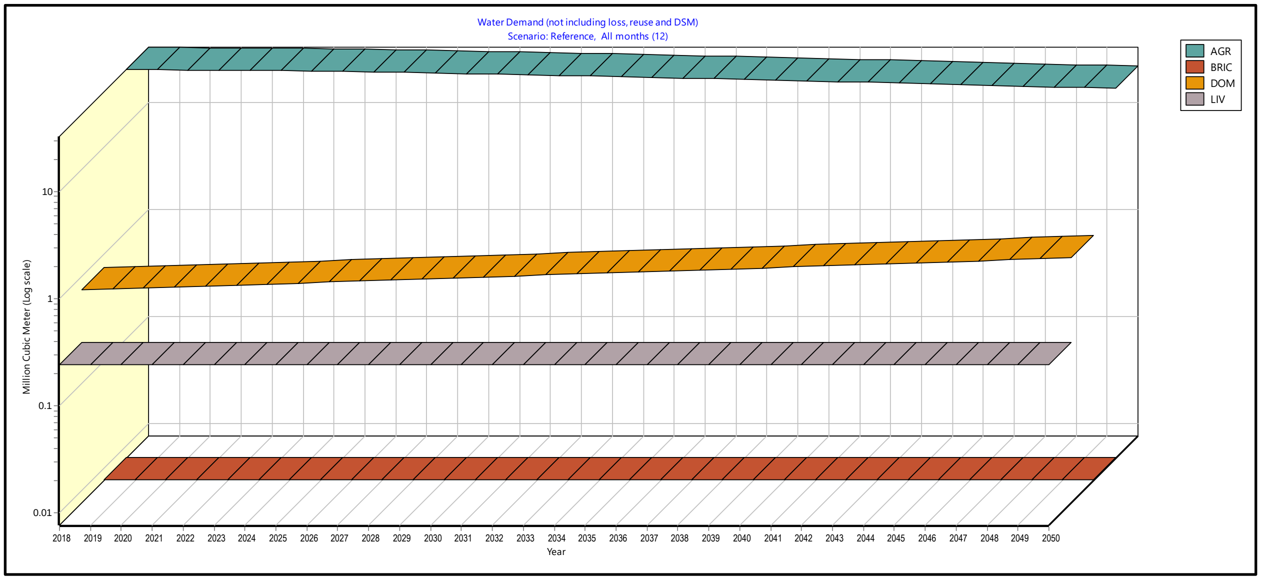


Figure 4.25: Annual total Water Demand (not including loss, reuse, and DSM)

4.4.1.2 Annual total unmet demand under irrigation systems improvement

The improvement of irrigation systems and an increase in normal population growth led to the remarkable total annual reduction of unmet demand for the different demands. These unmet demand reductions are such as: for agriculture decreased from 0.64MCM to 0.03MCM; domestic decreased from 0.02 MCM to 0MCM (100% coverage), and livestock keeping demand decreased from 0.01MCM to 0MCM from the year 2018 to 2050 as shown in the Figure 4.26.

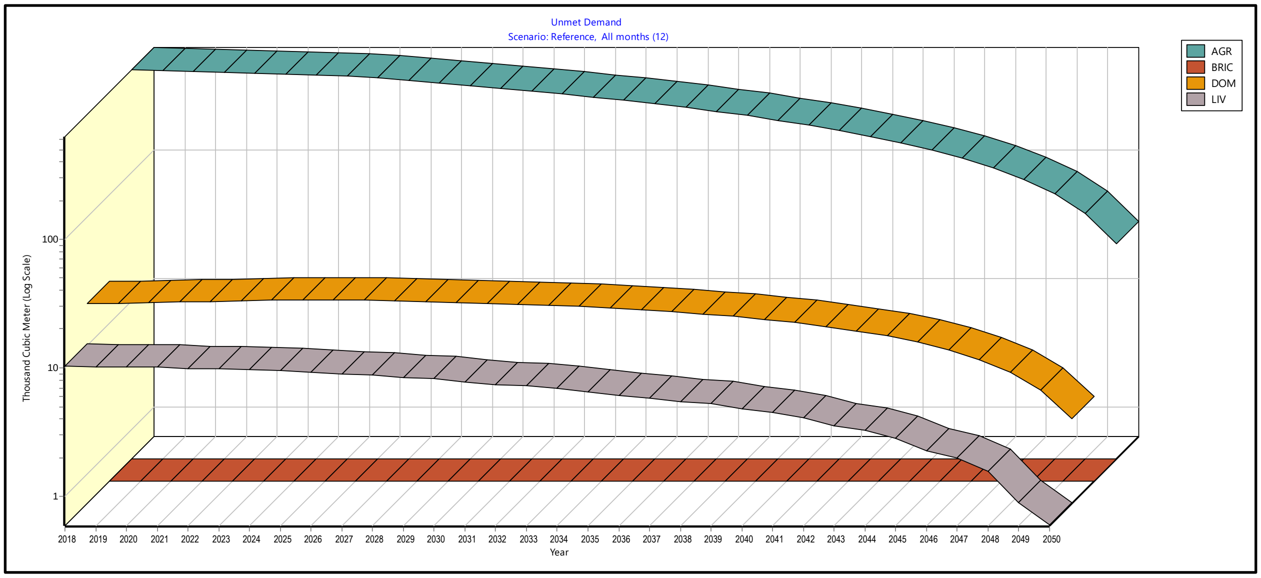


Figure 4.26: Annual total unmet demand under irrigation improvement

4.4.2 Scenario: High Population Growth

The construction of Lugoda is expected to increase the economic activities in the basin due to availability of water for irrigation, fishing activities in the dam, reliable power supply from the dam, and other economic infrastructures expected to be improved in the basin. This will eventually attract migration of people to the basin hence increasing the population of the area. The increase in population increases domestic, agricultural, bricks making, and livestock watering demand.

This scenario examined the impact of high population growth on domestic water demand in Madibira ward from a rate of 2.2% to 2.8%. Figure 4.27 show that the total annual water demand will increase substantially from 0.75Mm^3 (2.2%) and 0.77Mm^3 (2.8%) in 2018 to 1.45Mm^3 (2.2%) and 1.8Mm^3 (2.8%) in 2050.

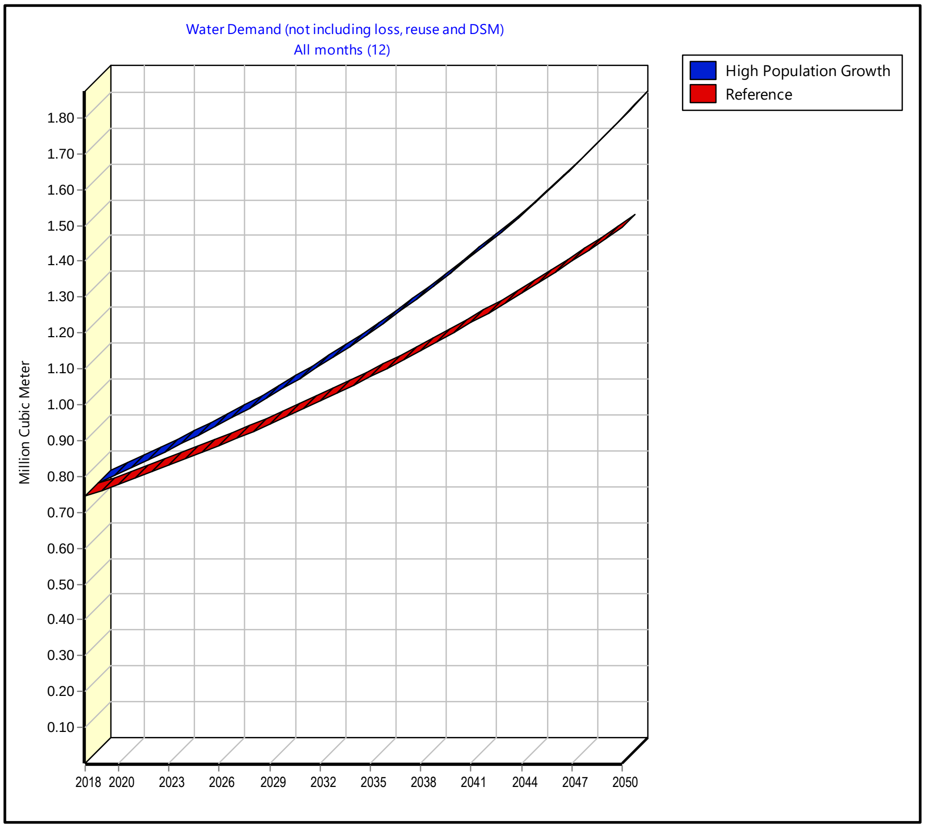


Figure 4.27: Comparisons of domestic water demand under high population increase (2018 - 2050) and reference scenario

4.4.2.1 Annual Total Unmet Demand Under High Population Growth Scenario

The high population increase in the basin led to high water demand. The study showed that the limited amount of water available in the river flow is not able to accommodate the demand resulted by the high population. The linear increase in unmet demand have been registered from 2024 (580 to 600TCM) to 2050 (20 to 30TCM) under reference and high population scenarios, respectively (Figure 4.28).

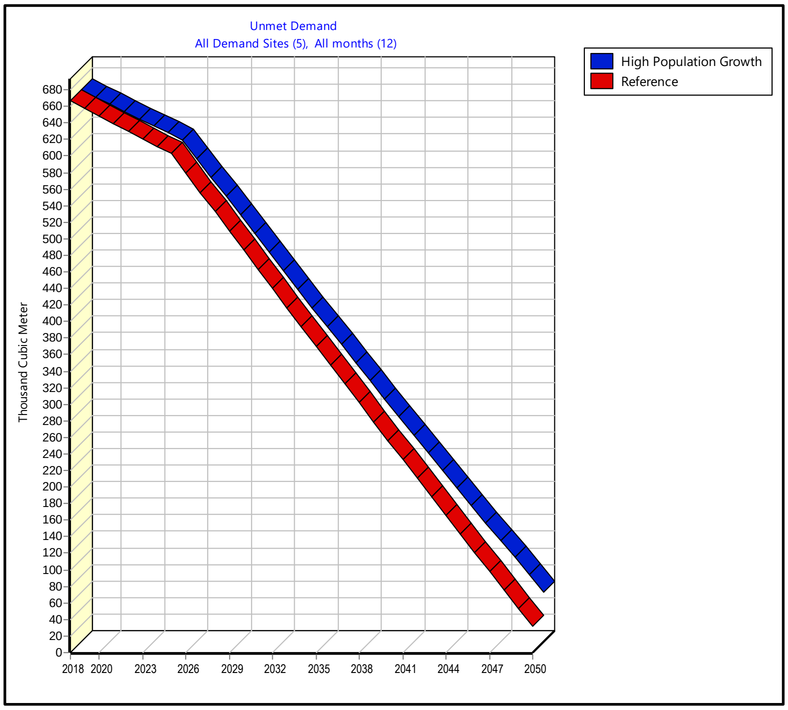


Figure 4.28: Annual Total Unmet Demand for all demand sites Under High Population Growth Scenario

4.4.3 Change of demand priority for Agriculture from 4 to 5

The change of demand priority for irrigation resulted into unmet demand for domestic and livestock to decrease to 0% (i.e., demands for these sectors is covered 100%), while the demand for agriculture increased hence increasing the unmet demand as shown in the Figure 4.29.

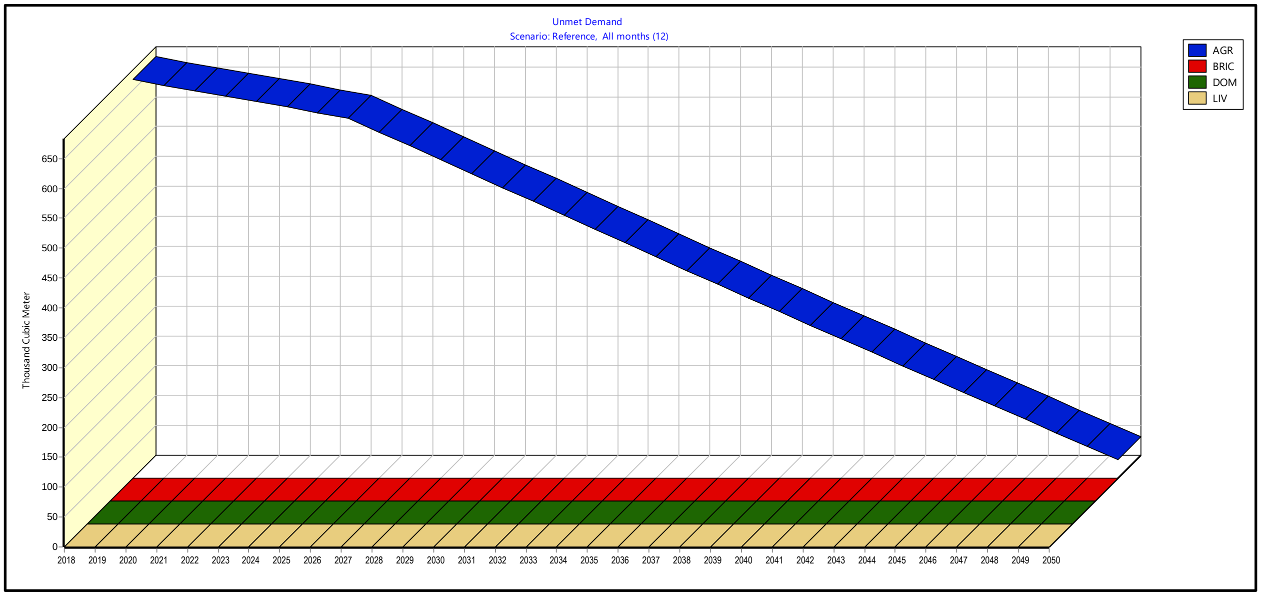


Figure 4.29: Unmet demand for all sectors under a change in Agricultural water supply priority scenario

4.4.4 Construction of Lugoda Reservoir in Ndembera river Scenario

The aim of introducing the construction of Lugoda dam was to be used to store water during the wet period where floods occur. The water stored will help to supplement the water demand during the dry period. Lugoda dam will also release 2MW of electricity which is expected to boost the social-economic investment in the catchment and other areas in the country. Fishing activities are also likely to be boosted.

Hence, considering the importance of dam for irrigation investments, the integrated development of hydropower and socio-economic infrastructure will be an input to provide an integrated rural development program to boost the local economy and reduce poverty.

4.4.4.1 Reservoir Inflows and Outflows for all demand sites

The reservoir water balance is controlled by different processes. The inflows and outflow of reservoir water were found to mainly be influenced by inflow from upstream, outflow to downstream and net evaporation. The increase in reservoir storage was observed to occur from January to April during the wet season when the river flow in the catchment is high. Net evaporation was found to increase from the wet season to dry season hence leading to water loss from the reservoir and river flow. The decrease in reservoir storage increases during the dry period (September to November) were evaporation become high, and pressure in water demand for irrigation, domestic, livestock watering and bricks making water demands increases (Figure 4.30).

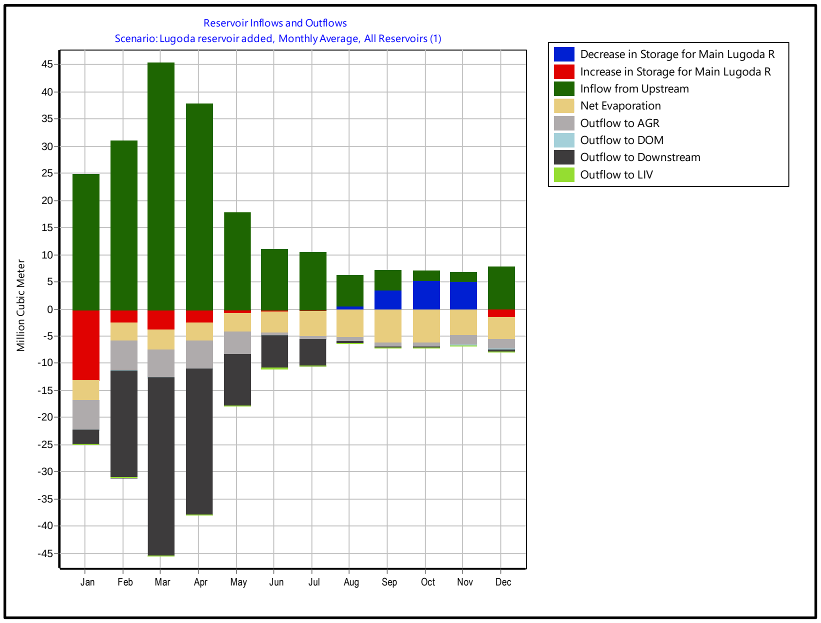


Figure 4.30: Monthly average Lugoda Reservoir Inflows and Outflows

4.4.4.2 Demand Site Coverage for Agriculture after implementation of Lugoda Reservoir

The year 2020 has been set as the reservoir startup year in the WEAP system.: This means that 2018 and 2019 have been regarded as construction and reservoir filling periods while the operation of the reservoir is to commence in 2020. The study found that construction of Lugoda dam is expected to increase water demand coverage for the agriculture sector in November from 80.87% (before the reservoir has been built) to 98.17% after implementation of the reservoir. From the study (Figure 4.31), it was revealed that water supply from the reservoir to demand sites was able to cover for 100% from January to October which is contrary to before reservoir construction (reference) where unmet demand began in September to November.

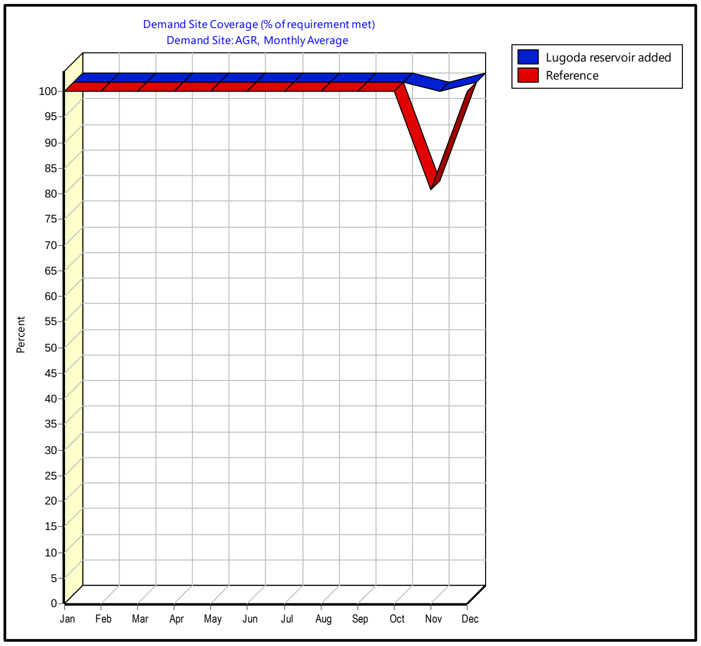


Figure 4.31: Demand Site Coverage for Agriculture after implementation of Lugoda Reservoir

4.4.5 Introduction of Environmental flow requirements for RNP

To meet the Ecological requirement for RNP, the EFR demand site was given priority 1. This means that in model simulations, priority was given to meeting demands in preference to filling reservoirs. The reservoir monthly release variation in the WEAP system was assigned. High water release was set to be occurring during the dry period where the flow of the river reduces (Table 4.11). The introduction of the reservoir as a source of downstream flow regulation has shown that the instream flow required increased drastically from August to November when the high demand for the water for ecology occurs (Figure 4.32).

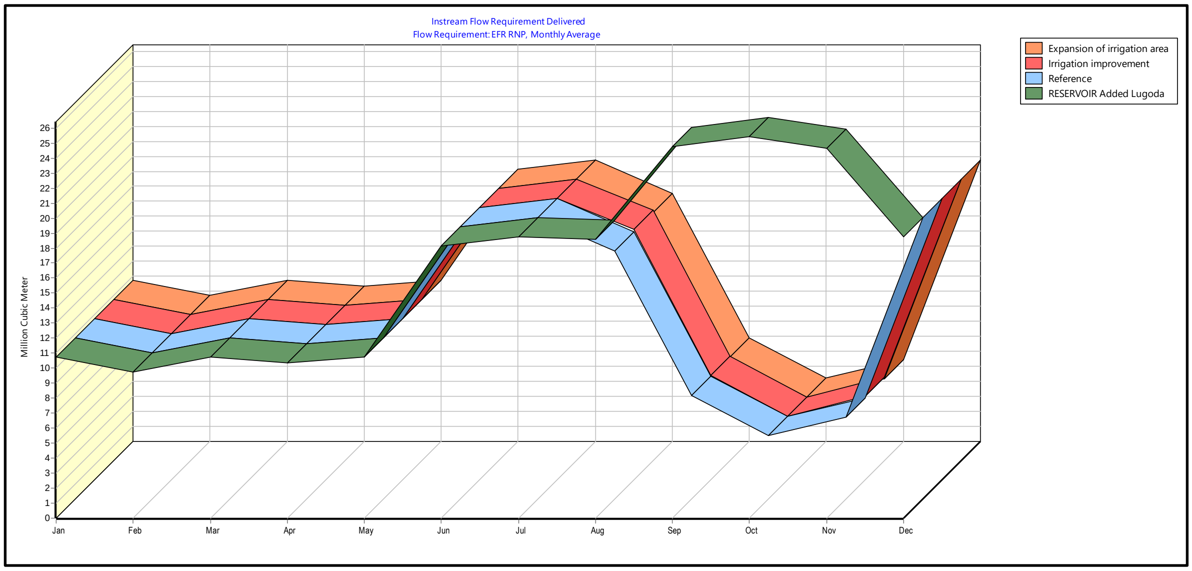


Figure 4.32: comparison of average monthly instream flow requirement delivered under reference scenarios

4.4.5.1 Demand Site Coverage (% of requirement met) under EFR Scenario

The introduction of environmental flow requirement from the Lugoda reservoir has compromised the water coverage to all other four water demand sites in the catchment. Table 4.11 shows that during the dry season the water coverage in agricultural, domestic. Livestock and brick-making sectors have reduced from 100% June to 95% in November. Also, the study revealed that due to the high water demand required to sustain the ecological water supply to the RNP. This is because EFR water released from the reservoir has to account for water loss taking place during the river flow and in the Ihefu swamp. This led to an increase in unmet demand for other sectors compared to before introducing the EFR (Figure 4.33) where the unmet demand occurred only in October to November. Thus, the study indicated that the construction of Lugoda dam only is not reliable for sufficiently supplying water to all demand sites in the catchment. The results found in this study are different from the results obtained by SMUWC (2001) where the dam was found to be sufficient to cover the demand for all in the catchment.

Table 4.11: Average monthly demand sites requirement coverage under EFR scenario

Demand sites	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Agriculture (%)	100	100	100	100	100	100	100	98.43	97.56	97.24	95.86	100
Bricks making (%)	100	100	100	100	100	100	100	98.54	97.6	97.26	100	100
Domestic use (%)	100	100	100	100	100	100	100	98.43	97.57	97.24	95.92	100
Livestock (%)	100	100	100	100	100	100	100	98.43	97.57	97.24	95.88	100
EFR (m^3/s)	4	4	4	4	4	7	7	7	10	10	10	7

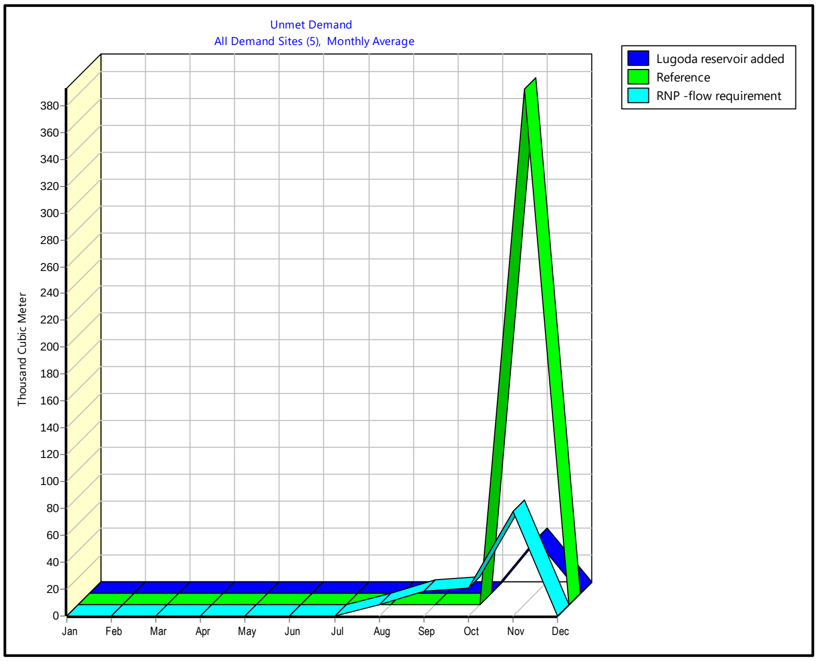


Figure 4.33: Unmet demand sites under different scenarios

4.4.6 Water Demand Site Management (DSM) Scenario and expansion (phase II) of irrigation area by 100%

Considering the high importance of agriculture for improving the economy, alleviating poverty, improving health and social wellbeing of the people and country as a whole, the Madibira irrigation scheme has planned to expand the irrigable land twice to the current area 4000ha (Phase I). The Madibira phase II (8000ha) is expected to be implemented after the construction of the Lugoda dam. The expansion of the irrigable land considered the water demand site management (DSM) in the irrigation activities. This aimed at reducing the water abstraction from the river and efficiently utilization of water abstracted, especially in the dry period where water becomes scarce. Table 4.12 shows the DSM saving was applied from June to November. The study revealed the occurrence of unmet demand (all demand sites except brick making) in November and January where water release from the reservoir is limited (i.e. January is the period for filing the reservoir) set in the system. These results correlate with the results obtained by the study reviewed, where the 100% expansion of irrigation area was not met by relying on water from the river and Lugoda dam.

Table 4.12: Demand sites coverage under DSM saving scenario

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AGR (%)	98.62	100	100	100	100	100	100	100	100	100	97.58	100
BRIC (%)	100	100	100	100	100	100	100	100	100	100	100	100
DOM (%)	98.64	100	100	100	100	100	100	100	100	100	97.59	100
LIV (%)	98.65	100	100	100	100	100	100	100	100	100	97.6	100
DSM SAVING VALUE (%)	0	0	0	0	0	40	50	60	60	60	30	0

4.4.7 Expansion of Phase I irrigation area by 50%

The reduction of the expanded irrigation area from 8000ha to 6000ha increased the coverage of all demand sites from 97.58 to 98.06% for agriculture, 97.59% to 98.07% for domestic use, and 97.6% to 98.08% for livestock watering. Due to the little amount of water demanded by bricks making sector and being given the first priority of supply, the changes in the agricultural area had not affected this sector. Moreover, due to high supply of water from the reservoir to demand sites during the dry period, shortage of water has been found in November which fails to meet the demands to agriculture, domestic and Pastoralism (Figure 4.34). The study results resemble with the reviewed work conducted in the catchment where the expansion of irrigation area by 50% was not able to cover meet 100% water demand for irrigation.

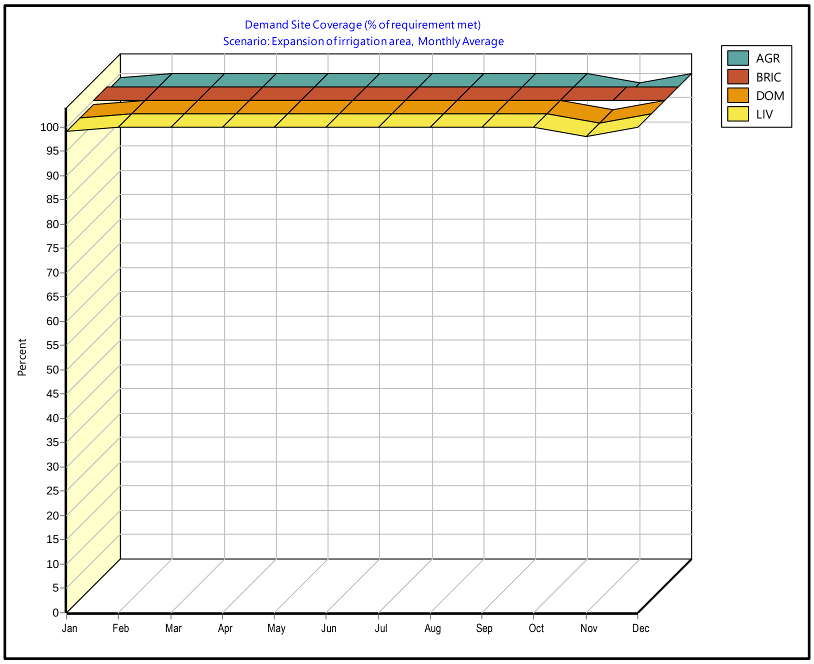


Figure 4.34: Demand sites coverage under irrigation area expansion scenario.

4.4.8 Construction of Ndembera reservoir (Small Lugoda reservoir) scenario

The study showed that construction of Lugoda dam could not be able to meet all the demands under high water demand pressure. The construction of another dam (half capacity of the Lugoda dam) down the Lugoda dam in the Ndembera river will enable the coverage of EFR downstream, especially to RNP. Figure 4.35 shows that the construction of Ndembera reservoir from 2018 to 2019 will ensure 100% water requirement for environmental flow and other demand sites to be met from 2020 to 2050.

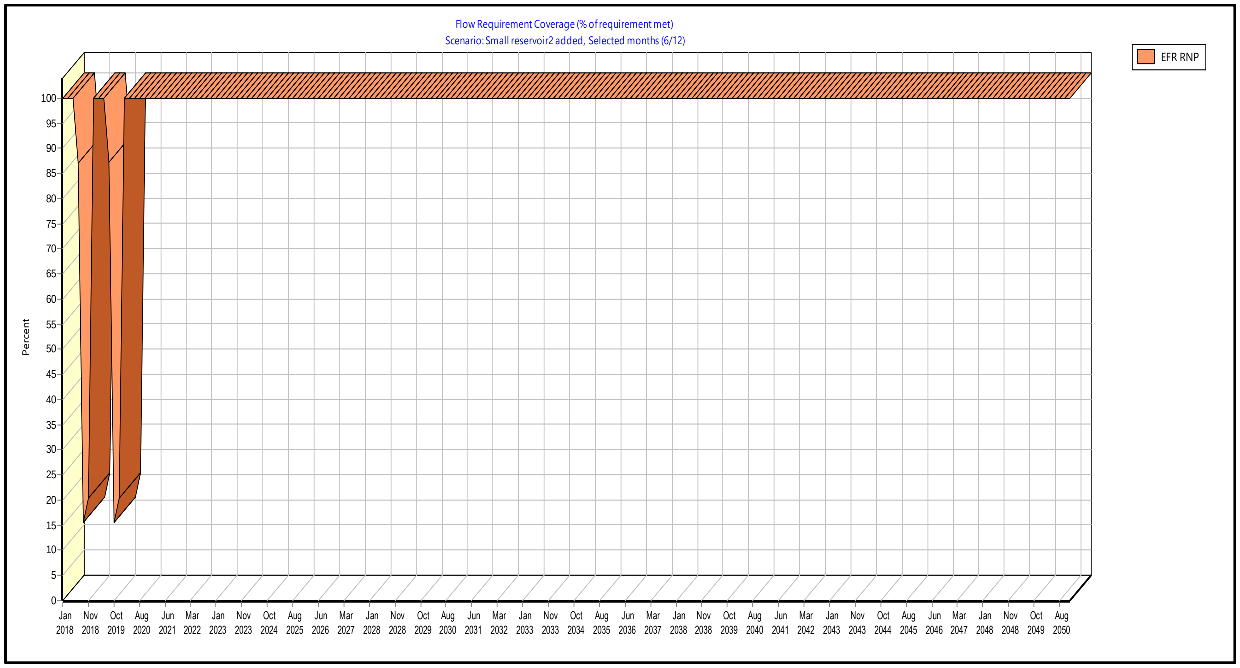


Figure 4.35: Ecological flow requirement coverage scenario when construction of Ndembera dam is implemented

4.4.9 Impoundment of Ihefu Swamp

Ihefu is the perennial swamp with an average area of 80km². This swamp is always shallow or relatively even depth (i.e. at the bottom), and the maximum depth is 2.5m. Water flow is obstructed by the high vegetation density which accounts for about 30% of the volume of the swamp. Evapotranspiration accounts for 22% of the water loss in the swamp. As inflow increases in the wet season, the wetland fills and an outflow results over the rock bar which is averaged to 1.5m deep at N'griama, thus generating the flow in the GRR downstream. The construction of water sill of 1m high on the rock and introduction of weirs at the outlets will increase the volume of water storage and help to regulate the water flow during the dry period. Considering the dead volume of about 40Mm^3, volume reduction due to vegetation coverage and evaporation, the swamp will have an active volume of about 28Mm^3. This volume can enable the supply of water for five months of the dry season for a flow rate of $1.543m^3/s$ downstream hence helping to supply water to RNP (EFR).

4.5 Groundwater abstraction option

Groundwater abstraction has been investigated for the purpose of being used either for domestic purposes, restoration of GRR flow in RNP or used for irrigation activities during the dry season. The study conducted by SMUWC revealed that the hydrogeology of the basin is largely unknown in terms of both groundwater quality and quantity. The pumping tests conducted by SMUWC (2001) in the alluvial sediments of the fans were found to be the only reasonable aquifer with groundwater. The test revealed a low abstraction rate of 1 – 5 l/s. Based on this low abstraction rate, the study realized that to achieve at least $1m^3/s$ the sustainable supply of water for ecological flow in the RNP or irrigation sector will require multiple boreholes. Thus, considering various infrastructural limitations such as borehole drilling and the cost of energy required to power the pumps are highly found to be the limiting factors for the option to be feasible. Moreover, the option is more questionable due to its high cost of maintaining the number of boreholes as well as environmental issues of having hundreds of boreholes in the national park makes the option unfeasible.

Sustainability of the option is also highly questionable, given the cost of energy required, the maintenance cost of a large number of boreholes needed and water quality-related impacts associated with the extensive abstraction required. Finally, the environmental impact of several hundred boreholes in the RNP makes this option entirely unfeasible. The options could only be feasible for domestic water use, particularly the tail-enders, which requires a small amount of water. This could also help to reduce the pressure of water abstraction, especially during the dry period. Due to these factors, the option had not been subjected to further analysis using the WEAP model.

4.6 Impoundment of the GRR tributaries within RNP option

The impoundment of the small rivers found within RNP has been investigated during the study. These GRR tributaries are mainly found downstream of the N’giriama sill. The impoundment of these rivers was found to be feasible because less water storage will be required compared to impounding the Ndembera river. Among of the river found to be potentially suitable for impoundment were Mwagusi, Itiku, Mdonya. The significance of these rivers were based on their potentiality of having substantial wet season flow which is enough to fill the impoundment required to sustain a dry season 1 – 2 m^3/s release for ecological conservation in the RNP. However, these rivers were found to be flowing seasonally hence showing the potentiality of having high sediment loads during the rainy season flood flow events. This factor indicated that the ponds will be filled with sediments within a short period and hence becoming unsustainable.

4.7 Water quality

The study found that between 30% and 60% of the water abstracted from the river for irrigation activities is returned to rivers. Due to the high utilization of fertilizers, pesticides, and weed killers, the returned water from the farms to some extent is polluted with salts, fertilizers, and pesticides. This leads to water being of limited value to be used by other sectors. Additionally, water leach of excess nutrients from farms into water sources causes eutrophication, which damages the flora and fauna by producing algal blooms and depressing dissolved oxygen levels (Figure 2.1-D). Moreover, the increase in sediment loads in rivers arising from erosion of agricultural land has a negative impact on the downstream ecosystem which in turn leads to increase in siltation in downstream channels, wetlands, and other hydraulic infrastructures.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSION

All living things need water to survive. River's, stream's and wetland's water enables plants to grow and secures the survival of fish, mammals, and insects healthy. The water is also essential for people's basic needs as well as the livelihood of the poor. Thus, the water resources need to be used efficiently to ensure that it does not compromise these benefits.

Additionally, ecological flows of the river should be guaranteed to the GRR for sustainable management of GRR catchment and Ruaha National Park. From the study, it is evident that demand coverage of water abstractive uses especially in irrigation farming will reduce with the implementation of agricultural expansion area and environmental flows to RNP, especially in the current account scenario.

However, with an increase in water storage through the construction of Lugoda dam, the level of water coverage to the demand sites has increased, though the dry periods of August to November will still face scarcity. Also, the study showed that the improvement of the water abstraction infrastructures and irrigation techniques will reduce the water demand in the agricultural sector, hence allowing the reserve water to flow downstream. Moreover, implementation of other reservoirs in the Ndembera river and Ihefu swamp water storage, the coverage of the water demand, especially for ecological flow in the RNP will be achieved by 100%.

Other options would include the construction of runoff harvesting reservoirs in the RNP to supplement the ecological water demand during the dry period.

The findings of the study provide the recommendations to the management of GRR catchment in terms of implementing the reserve water rights in a timely manner and control of illegal water abstraction to ensure water management cost recovery and proper water allocation.

The river has been experienced changes in its flow regime. Thus, it is important to implement the catchment management strategy, particularly in groundwater data collection and analysis. The availability of groundwater information would enhance demand and supply analysis in the catchment. It was also noted that there are no water storage dams in the catchment which cause the water users to depend solely on river flow water in all seasons. Strengthened WRUAs may help to bring about self-regulation of water users.

WEAP system analysis results provided a basis for understanding needs and deriving practical and feasible options for restoring the yearly flow of GRR, hence enabling to sustain ecological water supply to RNP.

The system helps in water allocation decisions based on the priority given to a particular demand sector, especially in the basin where there are water competing users. Moreover, the user-friendly interface of the WEAP21 gives it an added capability of facilitating the dialogue among various stakeholders with interest in water allocation and management in the basin.

5.2 RECOMMENDATIONS

Due to poor utilization and management of water resources revealed from the study, the following recommendations are made in order to ensure the provision of sustainable water flow in the river:

- Water savings and rainwater harvesting is an important infrastructural development that should be well-emphasized and developed to put a step towards integrated environmental flow management.

- The study has found that illegal water abstraction structures and water theft are very common in the catchment, which affects the natural regulation of the river. Thus, for effective and sustainable management of the river flow, illegal abstractions should be taken seriously, and this issue has to be tacked together with the local population.

- The study has also found that much of the water is being used inefficiently, by both large- and small-scale rice farmers in Usangu plains, which leads to over-abstraction of water from the river. Therefore, it is recommended that irrigation efficiency should be improved through regulatory control and participatory management

- The delay of water rights and lack of limitation of the water right expire date was found to be among the cause of illegal water abstraction and water theft in the basin. Thus, Water rights should be established and properly administered (should be granted in a transparent and timely manner), and pollution standards should be established for the Usangu wetland.
- Water allocation should also be based on the command area or crop water requirements to maximize the efficient utilization of the water abstracted or allocated. This should go parallel with restricting the traditional rights, de facto rights, which lead to the allocation of inefficiently allocation/ abstraction of water during the peak flow period.
- Capacity building and awareness raising to water users in the catchment need to be conducted regarding the consequences of their actions on the wetland ecology, and the implication of this for the future of the wetlands and its users.
- There is also a need for capacitating/strengthening the local government organizations on how to manage water resources and the water-related environment in the Great Ruaha River landscape.
- RBWO with support of the ministry of water, environment, and tourism and with the support and collaboration with other stakeholders should arrange a workshop at which the findings of these different options for restoring the river flow can be shared and discussed, with the aim of finding the way forward for consultative implementation.

5.3 FUTURE RESEARCH

Additional research is required in the following areas:

- Considering the high utilization of fertilizers and pesticides in agricultural activities and other changes in management and social-economic activities that have taken place in the basin, there is an inevitable need of assessing the water quality of the GRR. This involves the analysis of the effects of fertilizers on the wetlands as well as understanding the sources, levels, and impacts of both organic and inorganic fertilizers, which may lead to eutrophication.
- Due to a shortage of data regarding the availability of groundwater in the basin, there is the need of assessing the potentiality of the groundwater in terms of both quality and

quantity so as to allow water basin management to use it as a source of water for different uses and users. This should go parallel with investigating the seepage, percolation and other forms of water losses in the basin.

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APPENDICES

A: Water demands Monthly variation by mathematical expression

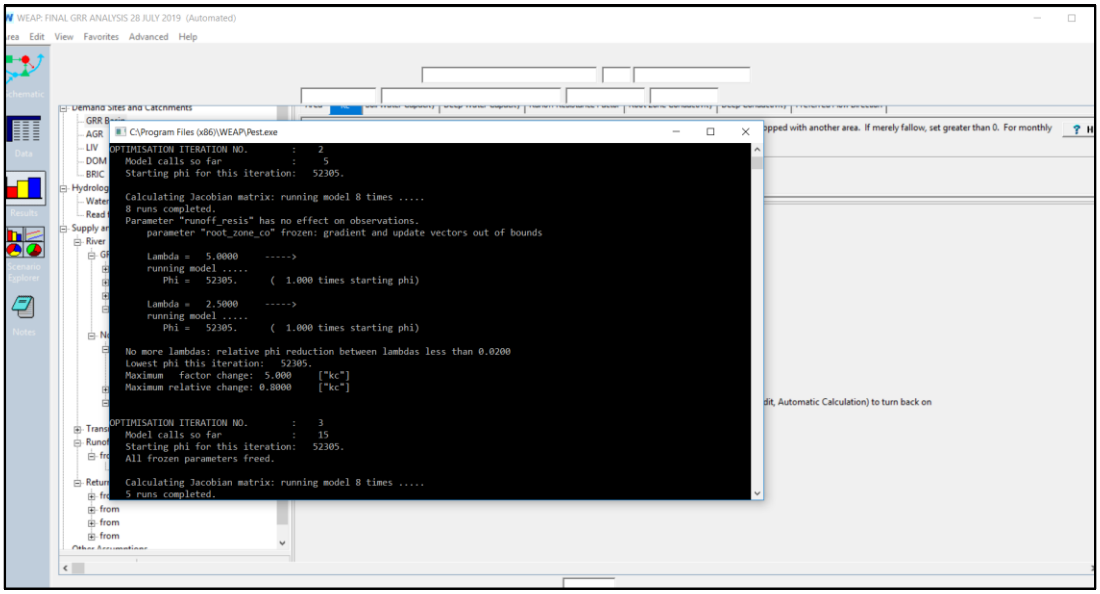
Annual total Water Demand (not including loss, reuse, and DSM)					
YEAR	**AGR**	**BRIC**	**DOM**	**LIV**	**Sum**
2018	33.2	0.01	0.75	0.045	34.005
2019	33.03	0.01	0.76	0.045	33.845
2020	32.86	0.01	0.78	0.045	33.695
2021	32.69	0.01	0.8	0.045	33.545
2022	32.51	0.01	0.81	0.045	33.375
2023	32.34	0.01	0.83	0.045	33.225
2024	32.17	0.01	0.85	0.045	33.075
2025	32	0.01	0.87	0.045	32.925
2026	31.6	0.01	0.89	0.045	32.545
2027	31.2	0.01	0.91	0.045	32.165
2028	30.8	0.01	0.93	0.045	31.785
2029	30.4	0.01	0.95	0.045	31.405
2030	30	0.01	0.97	0.045	31.025
2031	29.6	0.01	0.99	0.045	30.645
2032	29.2	0.01	1.01	0.045	30.265
2033	28.8	0.01	1.03	0.045	29.885
2034	28.4	0.01	1.06	0.045	29.515
2035	28	0.01	1.08	0.045	29.135
2036	27.6	0.01	1.1	0.045	28.755
2037	27.2	0.01	1.13	0.045	28.385
2038	26.8	0.01	1.15	0.045	28.005
2039	26.4	0.01	1.18	0.045	27.635
2040	26	0.01	1.2	0.045	27.255
2041	25.6	0.01	1.23	0.045	26.885
2042	25.2	0.01	1.26	0.045	26.515
2043	24.8	0.01	1.28	0.045	26.135
2044	24.4	0.01	1.31	0.045	25.765
2045	24	0.01	1.34	0.045	25.395
2046	23.6	0.01	1.37	0.045	25.025
2047	23.2	0.01	1.4	0.045	24.655
2048	22.8	0.01	1.43	0.045	24.285
2049	22.4	0.01	1.46	0.045	23.915
2050	22	0.01	1.49	0.045	23.545

B: Annual total unmet demand (MCM) under all scenarios

Year	Expansion of irrigation area	High Population Growth	Lugoda reservoir Scenario	Reference	RNP -flow requirement	SMALL LUGODA reservoir Added
2018	0.64	0.64	0.64	0.64	0.64	0.64
2019	0	0.63	0.63	0.63	2.85	0.63
2020	0	0.62	0	0.62	0	1.4
2021	0	0.61	0	0.61	0	0
2022	0	0.6	0	0.6	0	0
2023	0	0.59	0	0.59	0	0
2024	0	0.58	0	0.58	0	0
2025	0	0.57	0	0.57	0	0
2026	0	0.55	0	0.55	0	0
2027	0	0.53	0	0.52	0	0
2028	0	0.51	0	0.5	0	0
2029	0	0.48	0	0.48	0	0
2030	0	0.46	0	0.46	0	0
2031	0	0.44	0	0.43	0	0
2032	0	0.42	0	0.41	0	0
2033	0	0.4	0	0.39	0	0
2034	0	0.37	0	0.37	0	0
2035	0	0.35	0	0.34	0	0
2036	0	0.33	0	0.32	0	0
2037	0	0.31	0	0.3	0	0
2038	0	0.29	0	0.28	0	0
2039	0	0.27	0	0.26	0	0
2040	0	0.25	0	0.24	0	0
2041	0	0.23	0	0.21	0	0
2042	0	0.21	0	0.19	0	0

2043	0	0.19	0	0.17	0	0
2044	0	0.17	0	0.15	0	0
2045	0	0.15	0	0.13	0	0
2046	0	0.13	0	0.11	0	0
2047	0	0.11	0	0.09	0	0
2048	0	0.09	0	0.07	0	0
2049	0	0.07	0	0.05	0	0
2050	0	0.05	0	0.03	0	0
Sum	0.64	12.16	1.26	11.87	3.49	2.66

C: WEAP PEST CALIBRATION AND VALIDATION ANALYSIS



```
OPTIMISATION ITERATION NO.        :    2
   Model calls so far             :     5
   Starting phi for this iteration:   52305.

   Calculating Jacobian matrix: running model 8 times .....
   8 runs completed.
   Parameter "runoff_resis" has no effect on observations.
       parameter "root_zone_co" frozen: gradient and update vectors out of bounds

       Lambda =   5.0000     ----->
       running model .....
          Phi =   52305.      (  1.000 times starting phi)

       Lambda =   2.5000     ----->
       running model .....
          Phi =   52305.      (  1.000 times starting phi)

   No more lambdas: relative phi reduction between lambdas less than 0.0200
   Lowest phi this iteration:   52305.
   Maximum   factor change:  5.000     ["kc"]
   Maximum relative change: 0.8000     ["kc"]


OPTIMISATION ITERATION NO.        :    3
   Model calls so far             :    15
   Starting phi for this iteration:   52305.
   All frozen parameters freed.

   Calculating Jacobian matrix: running model 8 times .....
   5 runs completed.
```