

**INVESTIGATION OF HYDROLOGIC CARRYING CAPACITY AND
ASSOCIATED WATER PRODUCTIVITY FOR WATER RESOURCES
ALLOCATIONS: A CASE OF KILOMBERO RIVER CATCHMENT,
TANZANIA**

Onesmo Zakaria

**A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Hydrology and Water Resources Engineering of the
Nelson Mandela African Institution of Science and Technology**

Arusha, Tanzania


July, 2025

ABSTRACT

The world over, water resources availability is in decline while population and associated water demands are in an increase. This limits the capacity of hydrologic catchments to sustain the growing economic activities. In this regard, the productivity value of water (PVW) is increasingly gaining popularity among water resources managers as a tool for water allocation. Studies on PVW help to complete the Integrated Water Resources Management Pillars i.e., the famous 3E's (Equity, Economic/Efficiency and Ecological Integrity) by assessing the value of water beyond just the equity principle that only concentrates on the fair volumetric share of water. However, PVW concept is at its nascent stage characterized by a lack of a knowledge and tools to relate water resources and the economy it propels. The current study therefore, began by assessing catchment hydrologic carrying capacity and delved into assessing PVW after which a marginal productivity of water (MPW) was assessed to determine increasing or diminishing return for every change in water use. These were preceded by an analysis of hydrologic carrying capacity of the catchment where non-parametric Mann-Kendall (MK) statistical tests as well as the Soil and Water Assessment Tool (SWAT) were applied. These helped to assess climate trend and model the interaction of hydrology, climate and land use/cover changes and their implication to water availability. The results showed that the historical hydrologic parameters were favorable whereas the future painted a stressful scenario ($p < 0.05$). Given the increased expansion of thirsty sectors of economy, the seemingly increasing river discharge at Swero (1KB17) gauging station was attributed to sediment deposition with annual losses of 42.13 Tonnes/Ha in 2021 to a projected sediment loss of 43.95 Tonnes/Ha in 2041. Furthermore, findings on productivity of water showed that paddy had low PVW (0.01 USD/m³) compare to Sugarcan (0.10 USD/m³) and Hydroelectric production (0.19 USD/m³). However, the sub-sector is the most impactful in terms of food and employment security. On these bases, deliberate support and protracted capacity building and advocacy for the rainfed system of rice intensification (SRI) is recommended as a plausible paddy farming system which also had good PVW (0.11USD/m³). This study also recommends assessment of the value of water for the environment as an important sector as well as across the value chain for all sectors. Finally, the study recommends improvements in enforcing both water and LULC plans to ensure controlled expansion of economic activities that sustains the catchment performance.

DECLARATION

I, Onesmo Zakaria do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is my original work and has neither been submitted nor being concurrently submitted for degree award in any other institution.


Onesmo Zakaria

06th July 2025


Date

The above declaration is confirmed by:


Dr. Juma Rajabu Selemani

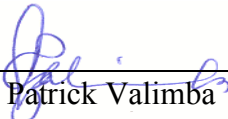
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Prof. Reuben M. J. Kadigi

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Date


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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Senate of the Nelson Mandela African Institution of Science and Technology a dissertation titled “*Investigation of Hydrologic Carrying Capacity and Associated Water Productivity for Water Resources Allocations: A Case of Kilombero River Catchment, Tanzania*” in partial fulfilment of the requirement for the award of the degree of Doctor of Philosophy in Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania.



31st July 2025

Dr. Juma Rajabu Selemani

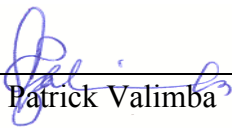
Date



07th July 2025

Prof. Reuben M. J. Kadigi

Date



07th July 2025

Dr. Patrick Valimba

Date

ACKNOWLEDGEMENTS

First and foremost, I would like to thank the Almighty God for the grace and courage to take up a PhD challenge that was implanted knowingly or unknowingly by my late Parents: Mrs. Tabia and Mzee Zakaria Sigalla - the shrewd entrepreneurs whose vision is unparalleled. How I wish you were here to gauge the work of your own hands. I am greatly indebted to my supervisors: Dr. Juma R. Selemani, Prof. Reuben M. J. Kadigi and Dr. Patrick Valimba for encouragement, guidance and introduction to new concepts.

I am greatly indebted by WISE Futures African Centre of Excellency for a substantial financial support without which school fees, and portion of upkeep and field work could not be possible. Dedicated appreciations go to you through the Centre's Leader, Prof. Hans Komakech for introducing me to this support and the larger NM-AIST as an institution and a professional family.

To my wife Dr. Kigocha Okeng'o and kids Ms. Caroline and Mr. Onesmo Sigalla Jr - I have a debt that can't be repaid for the amount of family time this study took. I am equally thankful to my siblings Ms. Rebecca, Ms. Grace and Ms. Debora Sigalla whose prayers and blessings kept me going. Similar appreciations go out to my friends both in and out of classrooms – you afforded me a smile when things got the hardest. All of you are sent from heaven – if it was for me, you would have had the longest chapter in this work. I leave you with Proverb 17:17.

DEDICATION

This research work is dedicated to my late parents Mrs. Tabia Nyambo Sigalla and Mzee Zakaria Aron Sigalla

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LIST OF ABBREVIATIONS AND SYMBOLS

'	Minute
:	Following
</>	Less than or Greater than
Δ	Change in
Σ	Sum
ARS	Agriculture Research Service
BCM	Billion Cubic Meters
BCM	Billion Cubic Meters
Bm ³	Billion Cubic Meters
BULT	Built-up Area
CA	Cellular automata
CEG	Computable General Equilibrium
CHIRP	Climate Hazards Group InfraRed Precipitation
CTFS	Conventional Transplant and Flooding System
CULT	Cultivated land
CUSUM	Cumulative Sum
DEM	Digital Elevation Model
e- /e+	Exponent and power sign
E _T	Evapotranspiration
ET _C	Crop Evapotranspiration
ETM	Enhanced Thematic Mapper
EVW	Economic Value of Water
FAO	Food and Agriculture Organization
FGD	Focused Group Discussions
FRSD	Woodland
FRST	Forest
GCM	Global Circulation Model
GDP	Gross Domestic Product
GHM	Global hydrological model
GIS	Geographic Information System
GPM	Gross Profit Margin
GRRC	Great Ruaha River Catchment

GWh	Gigawatt-hour
Ha	Hectors
HBV	Hydrologiska Byråns Vattenbalansavdelning
HEM	Hydro-Economic Models
HEP	Hydroelectric Production
HH	Household
HHS	Household Survey
HRU	Hydrologic Response Unit
HSPF	Hydrological Simulation Program Fortran
IDW	Inverse distance weighting
IFPRI	International Food Policy Research Institute
IQR	interquartile range
IWRMD	Integrated Water Resources Management and Development
JJA	June July August
KB	Kilombero Basin
KIA	Kappa Index of Agreement
KII	Key Informant Interview
KPL	Kilombero Plantations Limited
KRC	Kilombero River Catchment
KSCL	Kilombero Sugar Company Limited
KV	Kilombero Valley
kWh	Kilowatts-hour
LC	Land Cover
LU	Land Use
LULC	Land use Land cover
MAE	mean absolute error
MAX	Maximum
ME	Mean Error
MET	Meteorological
MIN	Minimum
MK	Mann-Kendall
MoW	Ministry of Water
MPV	Marginal Productivity Value

MSE	mean squared error
MW	Megawatt
NAWAPO	National Water Policy
NBS	National Bureau of Statistics
NM-AIST	Nelson Mandela - African Institution of Science and Technology
OCK	ordinary co-kriging
OK	Ordinary Kriging
OND	October November December
ORH	Observational-Reanalysis Hybrid
PA	Producer Accuracy
P_{eff}	Effective Precipitation
PET	Potential Evaporation
P_{month}	Monthly Precipitation
PRA	participatory rural appraisal
PVW	Productivity Value of Water
PWP	Physical Water Productivity
Q ₁ , Q ₂ , Q ₃	Quartile 1, Quartile 2 and Quartile 3
RBWB	Rufiji Basin Water Board
RIA	Residual Imputation Approach
RMSE	root mean squared error
RNGB	Bush land
RNGE	Grassland
ROI	Return on Investment
RRB	Rufiji River Basin
RS	Remote Sensing
s	second
SAGCOT	Southern Agricultural Growth Corridor of Tanzania
SAM	Segment Anything Model
SDYLD	Sediments Yield
SRI	System of Rice Intensification
SRTM	Shuttle Radar Topography Mission
SSA	sub-Saharan Africa
SWAT	Soil and Water Assessment Tool

SWAT	Soil and Water Assessment Tool
TANESCO	Tanzania Electricity Supply Company
TAZARA	Tanzania and Zambia Railway Authority
TM	Thematic Mapper
TMA	Tanzania Metrological Authority
TVP	Total Value of Product
TW	Transient Walk
TZS	Tanzanian Shillings
UA	User's Accuracy
UN	United Nations
UNESCO	United Nations Education Science and Culture Organization
URT	United Republic of Tanzania
US	United States
USD	United States Dollar
USDA	United States Department of Agriculture
USGS	United States Geological Society
UTM	Universal Transverse Mercator
VEO	Village Executive Officer
viz	videre licet = namely
VMP	Value Marginal Product
WATR	Water
WB	World Bank
WEF	Water Energy and Food
WEF	Water, Food and Energy
WEO	Ward Executive Officer
WETN	Wetland
WMO	World Meteorological Organization
WP	Water Productivity
WREM	Water Resources Engineering and Management
WRG	Water Resources Group
WRM	Water Resources Management
WUA	Water Users Association
WUE	Water Use Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Water flows across landscapes and provides multiple benefits to various inhabitants and the environment. These benefits include but are not limited to: Hydroelectric generation, key inputs to agriculture, ecosystem integrity, cultural and recreational benefits, habitats, and breeding sites for different species (Dudgeon *et al.*, 2006; Tickner *et al.*, 2017; Henderson & Loreau, 2023). In Tanzania, for instance, water resources have been significantly used in hydro-electric production (HEP) at Mtera, Kidatu, Kihansi, Nyumba ya Mungu, Hale, New Pangani Falls and Nyerere with the installed potential of 100 MW, 200 MW, 180 MW, 8 MW, 21 MW, 68 MW and 2115 MW, respectively (Cavestro, 2003; Mdee *et al.*, 2018; Haulle & Ndimbo, 2024). Following the introduction of Nyerere HEP, the current hydropower generation potential yields a surplus of about 675 MW compared to the existing generation capacity from all sources (International Energy Agency, 2014).

The HEP offers a source of power that is the cheapest, cleanest, and most responsive to grid turbulence (Kichonge *et al.*, 2015; Schmietendorf *et al.*, 2017). Additionally, water has been used to irrigate 460 000 ha of land in Tanzania with the area under irrigation estimated to amount to 1 million ha by 2025 (Palmer-Jones & Lankford, 2017). Water resources also play a vital role in wildlife conservation and hence tourism e.g., in the Ruaha, Mikumi, Serengeti, and Tarangire National Parks (Epaphras *et al.*, 2008; Stommel *et al.*, 2016; Wolanski *et al.*, 1999). Water resources also provide sanctuary to some species, e.g., the Kihansi spray toads that are endemic to Tanzania (Channing *et al.*, 2006; Mombo *et al.*, 2011).

However, the status of water resources has been declining in Tanzania from 2700 m³ per person per annum in 2001 to 2000 m³ per person per year in 2012 (United Republic of Tanzania [URT], 2018). The published data by the World Bank indicate that, the annual per capita water resource availability averaged at 1608 m³ in 2015 (World Bank, 2017). This is well below the Falkenmark indicator for “water sufficiency” of 1700 m³ per capita per year (Falkenmark, 1989). Given that Tanzania and most of sub-Saharan Africa (SSA) have limited storage facilities, e.g., dams, their agrarian economy fluctuates with rainfall pattern (Kurukulasuriya *et al.*, 2006; World Bank, 2006a, 2006b). In the face of water availability projection of about 1400 m³ per capita per year by 2025 (URT, 2018; Sharma & Tiwari, 2024), growth targets in vision 2025 will inevitably be determined by how best we use our waters.

Furthermore, the adverse effects of climate change in these areas shows a possible increment in temperature which will be manifested to even more water needs and the changed water availability in space and time (Young & Loomis, 2014). These impacts of climate change coupled with population pressure will inevitably add more challenges regarding water resources management. Equitable allocations as well as consideration of sectors with high productivity value of water (Lévite & Sally, 2002). This is especially after accounting the amount needed for domestic uses and environment integrity (MoW, 2002).

Manifestation of declining water resources, is well presented by the water-energy-food (WEF) nexus which has always been a major challenge to water managers (Dong *et al.*, 2019; Engle *et al.*, 2011; Leck *et al.*, 2015). In the Great Ruaha River Catchment that borders the area of study focus, poor irrigation practices have impaired river flows to the detriment of the ecosystem, HEP and the economy at large (Water Resources Management International Inc (WREM) & Rufiji Basin Water Board [RBWB], 2013b). While scholars such as Epaphras *et al.* (2008), have indicated wildlife suffering and deaths due to the mentioned catchment impairment, the IWRM planning process by WREM and RBWB (2013b) indicated that, by 2010, HEP had dropped from a combined 2121 GWh/yr (design potential) to 1499 GWh/yr for Mtera-Kidatu complex in 2010 following a drop in water flow from natural 4.55 BCM/yr and 5.70B CM/yr for Mtera and Kidatu, respectively.

This substantial decrease in HEP output underscores the economic ramifications of catchment degradation, beyond the ecological costs already documented. This substantial decrease in HEP output underscores the economic ramifications of catchment degradation, beyond the ecological costs already documented. Furthermore, the report highlighted a concomitant rise in reliance on thermal power generation, a less sustainable and more costly alternative, further exacerbating the region's vulnerability to energy price fluctuations. The long-term implications of this shift, coupled with projected increases in water demand for irrigation and domestic use, necessitate a re-evaluation of current water resource management strategies, emphasizing a more integrated and ecologically sensitive approach. Failure to address these intertwined challenges risks further depletion of the catchment's resources, leading to potentially irreversible damage to both the environment and the regional economy.

The drop of water flow to Mtera and Kidatu was a result of a reduction by 2010 upstream water uses of 2.95 BCM/yr (35% reduction) and 3.95 BCM/yr (31% reduction) for the same facilities (WREM & RBWB, 2013a). Following this finding, the integrated water resources management (IWRM) Plan studies have proposed volumetric moratorium on any future water allocations.

In addition, water use efficiency (WUE) measures are also proposed on current uses in Great Ruaha catchment (WREM & RBWB, 2013a). These included the proposed heavy investments on lining of at least primary canals, introducing high-value but low water consuming crops and implementation of Water Resources Management Act, 2009 especially establishment and/or empowering water users associations to help in enforcing the law (WREM & RBWB, 2013a). Even with available equity considerations, water managers should be equipped with more tools that provide additional visualization of the impacts of their decision. For instance, together with volumetric approaches that stresses more on WUE, water productivity (WP) studies are taken to be more appropriate indicator of water system performance (Seckler *et al.*, 2003).

The WUE which is more related to physical WP, can be defined as a measure of a drop of water for a given product generated whereas, WP is defined as the physical amount or economic value of product derived from the use of a given unit quantity of water (Mdemu *et al.*, 2013; Molden *et al.*, 2003). The WP is increasingly becoming an important indicator for robust water resources management in the face of diverse socio-economic undertakings that uses water as a critical input of production (Mdemu *et al.*, 2013). Increasing WP to higher product physical output or value for each drop of water used can be an important mitigation for the ever growing water scarcity (Molden *et al.*, 2001; Watkins, 2006).

The emphasis on WP underscores the need to optimize not just the quantity of water used, but also the value derived from that water. This necessitates a shift towards irrigation techniques that minimize water loss and crop selection that maximizes yield per unit of water consumed. Furthermore, considering the environmental implications of water use is critical. Sustainable water management necessitates a holistic approach that integrates economic, social, and environmental considerations. For example, promoting water-efficient agricultural practices can reduce the strain on water resources, improve livelihoods for farmers, and protect aquatic ecosystems.

Similarly, investment in water infrastructure, such as rainwater harvesting and efficient water storage facilities, can enhance water security and resilience to climate change impacts. The integration of these strategies alongside enhanced visualization tools will empower water managers to make informed decisions that ensure equitable and sustainable water allocation for present and future generations. In SSA, there are inadequate studies that have focused on understanding economic incentives to challenge the status quo. Little is known about hydro-economic opportunities that would result from changing the current WEF nexus dynamics where upstream land uses have impaired critical investments and ecosystems (Kangalawe *et*

al., 2011; Yang & Wi, 2018). Economic investigations, or the knowledge and prediction of decision-making under situations of resource scarcity, are important during the planning, design, and management of water resource systems (Gardner, 1983). The consideration of economic, hydrologic, and engineering processes in water resources management decisions is gaining credence in recent years (Barthel *et al.*, 2012; Blanco-Gutiérrez *et al.*, 2013; Nakic, 2017; Sherafatpour *et al.*, 2019).

Hydro-economic models (HEMs) establish a framework to study catchment-level interactions (Alamanos *et al.*, 2020). However, the efficacy of a HEM hinges on robust catchment knowledge, which necessitates adequate and relevant data. The model's various components must be well-defined and comprehensively populated with data, including hydrology, infrastructure, area economics, supply and demand operations, and the impacts or interactions of different variables (Nakic, 2017). As such, the study aimed at establishing the true value of water and hydro-economic tradeoffs between and within water uses is needed at a hydrologic planning unit to help policy makers with tools based on an informed assessment of the relationship between water and a range of its uses.

The current study therefore employed a myriad of methodologies to eventually assess the optimal tradeoff that yields the most efficient results of the economic return for an additional drop of water applied. This provides water managers with a tool and another layer of information as they allocate water to different sectors. This is more important in catchments such as Kilombero, where although it represents only a fraction of the entire Rufiji basin (about 20%), the catchment contributes upwards of 62% of the total annual average water flow of 13.8 Bm³/yr (Mwalyosi, 1990; WREM & RBWB, 2013b).

The optimization component in these models is particularly critical, as it allows for the exploration of different allocation scenarios and their resultant economic outcomes. By incorporating economic principles into water management, we can move beyond solely hydrological considerations and towards a more holistic and sustainable approach. This is particularly relevant in regions facing increasing water scarcity and competing demands for water resources. A hydro-economic analysis can help identify the most efficient allocation strategies, ensuring that water is used in a way that maximizes economic benefits while minimizing environmental impacts. Furthermore, understanding the economic value of water in different sectors can inform pricing policies and incentivize more efficient water use practices. Such insights are vital for promoting long-term water security and sustainable development in data-scarce environments. The integration of economic considerations in water

resource management, therefore, becomes not just a desirable approach but a necessity for addressing the complex challenges of water scarcity and competing demands in the 21st century.

1.2 Statement of the Problem

Across the world, Integrated Water Resources Management (IWRM) practices are guided by the 3E's principle of equity, economic efficiency and ecological integrity (Shastri & Srivastava, 2013; Wellens *et al.*, 2019). In this regard, water allocations must be equitable to all users including the environment but also consider economic value of the resource during allocation decisions. However, since the promulgation of Tanzania's first national water policy in 1991 (MoW, 2002) and subsequent water sector reforms (Doering, 2005; MoW, 2021; URT, 2009), water allocation have always followed the precautionary principle (Fisher *et al.*, 2006; Kriebel *et al.*, 2001) where only equity and ecological integrity principles of IWRM (Agarwal *et al.*, 2000), have been the main focus. These are through IWRM plans moratoriums (WREM & RBWB, 2013a) or e-flow assertion as per different studies in Tanzania (e.g., Epaphras *et al.*, 2008; King & Brown, 2010; McClain *et al.*, 2013). However, while they help to address some of the mentioned IWRM principles, they miss to account for the economic efficiency principle that UN advocates and is enshrined in the fourth Dublin Principle on the economic value of water (Jønch-Clausen, 2004; Lubell & Edelenbos, 2013; Solanes & Gonzalez-Villarreal, 1999).

Recent attempts to address this gap have incorporated the WP function (Kadigi *et al.*, 2008; McCartney *et al.*, 2007; Yang & Wi, 2018). However, these scholars employed a simple methodology i.e., Change in Net Income (Hussain *et al.*, 2001). Although the approach contributed significantly to put to surface the consideration of value of water, it gave a lumped value of water in assuming it is the only input of production leaving others such as labour, land, and other capital functions (Kadigi *et al.*, 2008). This then limits its reliability for making decisions on cross-sectoral water allocations as an important economic indicator (MoW, 2002). This study therefore, aims at assessing the hydrologic limitation and productivity value of water as a tool for water allocation (Bello & Chiang, 1970; Chiang, 2005; Mdemu *et al.*, 2013; Young, 1996).

1.3 Rationale of the Study

Studies focusing on establishing catchment hydrologic carrying-capacity and associated hydro-economic tradeoffs help to establish water allocation thresholds that benefit both minimum flow and economic functions. This is because a well-designed allocation regime supports multiple policy objectives, including economic efficiency, innovation, and investment in water

use efficiency, and environmental performance. This is achieved by securing adequate flows to support ecosystem services, which also promotes economic prosperity by distributing the risks of water shortages among users. This study provides a framework for water managers to build on the volumetric approaches of water allocation following the equity principle and adds an economic perspective that now completes the whole continuum of IWRM principles when the PVW is also addressed.

It is on this basis that the current study intends to investigate the catchment carrying capacity from the interaction of climate, land use/cover and hydrology parameters and assess hydroeconomic trade-offs for a better water allocation strategy. This will help to account for the true value of water across the different sectors of the economy.

1.4 Research Objectives

1.4.1 General Objective

The general objective of the study was to investigate the hydrologic carrying capacity and associated water productivities across the key economic sectors for better water allocation strategies in Kilombero River Catchment, Tanzania.

1.4.2 Specific Objectives

This study had the following specific objectives:

- (i) To investigate the historical and future hydrologic and LULC pattern in Kilombero River Catchment.
- (ii) To characterize the effect of hydrologic and LULC interaction to hydrologic regime of the catchment.
- (iii) To quantify the productivity value of water across the key economic sectors in KRC for a better water allocation strategy.
- (iv) To evaluate hydro-economic trade-offs in cross-sectoral water allocation within KRC for optimal resource management.
- (v) To deduce the potential policy and management interventions that can be implemented to improve water allocation efficiency and address hydro-economic trade-offs in the

KRC, ensuring sustainable water resource management in the face of climate change and increasing water demands

1.5 Research Questions

This study was designed to answer the following questions:

- (i) How have the long-term trends in hydrologic and LULC parameters influenced water availability in the Kilombero River Catchment?
- (ii) What are the interaction effects between hydroclimatic variability and LULC change on hydrological processes over Kilombero River Catchment?
- (iii) What are the direct productivity values of water for each of the key economic sectors in the Kilombero River Catchment?
- (iv) What are the hydro-economic trade-offs associated with cross-sectoral water allocation in the KRC, and which allocation strategies offer the most optimal balance between economic efficiency, social equity, and environmental protection?
- (v) What are the potential policy and management interventions that can be implemented to improve water allocation efficiency and address hydro-economic trade-offs in the KRC, ensuring sustainable water resource management in the face of climate change and increasing water demands?

1.6 Significance of the Study

The upcoming water management approaches will shift from concentrating on developing new water sources to efficient utilization of existing ones that also allocate the resource equitably. However, the spatial and temporal changes in water availability and its values will increasingly dictate efforts to address water scarcity and reduce water conflicts. The need for understanding hydrologic trends and assessment of efficient water allocation trade-offs is paramount in areas with huge, planned commitments imposing water stress like in Kilombero River Catchment (KRC). To reduce these conflicts, for instance, in well understood catchments, the amount of water allocated to farming may be reduced during drought periods (as saved water) and transferred to meet industrial or municipal requirements whose PVW are higher than farming. However, a limitation is with the unknown impact on the management of temporal and spatial water resources transfer from one use to another without a systematic and quantitative

examination of the catchment in question. It is on these bases that the current study intends to establish the hydroclimatic limitations and productivity value of water along its different uses to build on the knowledge base such as the conventional volumetric water allocation which is currently in use.

1.7 Delineation of the Study

The current research focused on determining the hydroclimatic carrying capacity of the catchment and associated hydroeconomic tradeoffs that would add to the volumetric water allocation mechanism commonly used in Tanzania. It began with assessing the hydroclimatic and land use/cover trends and its combined implications on water availability in Kilombero River Catchment. The study then investigated the understanding of the economic returns of water along its different uses before considering hydroeconomic tradeoffs that would inform prioritization of water allocation. Data for the initial portion of the study used daily observed and satellite data running across more than three decades. In addition, social economic data were collected in two missions viz. dry and wet seasons to capture income and water uses for different sectors of the economy, especially farming and hydro-electric production (HEP). Farming considered only paddy and sugarcane which were found to be the major crops in the area. Following the results of hydroclimatic investigation and productivity value of water, tradeoffs were assessed to propose policy, operational, and research recommendations to aid sustainable water resources allocation and management in Tanzania and sub-Saharan Africa at large.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

2.1.1 Productivity Value of Water

The public policies and decisions in respect of the allocation of water always have significant economic consequences for households, communities, business enterprises and the ecosystem. It is not uncommon that across the world, water is often allocated to less valued uses, hence without any reaping of benefits, water quantity and quality continue to worsen, groundwater reservoirs are often overexploited, water-related ecosystem services receive insufficient attention and floods and droughts take an unnecessary severe toll on life and property (Young & Loomis, 2014). If climate change projections are reasonably accurate, increase in temperatures are expected to result in greater water demands and increase the variability in water supply (Sigalla *et al.*, 2023; Young & Loomis, 2014). The future population increase, and the negative effects brought about by the variable and changing climatic conditions are likely to aggravate the current water resources management challenges. Thus, it will be increasingly imperative for water managers and government agencies to understand the economic value of water in various alternative uses, enabling them to make the most of limited water supplies by efficiently allocating the available water to maximize its value to the broader community.

2.1.2 Water and Economy

Long term observation shows that, global water withdrawals are directly proportional to population growth as illustrated in Fig. 1 (FAO, 2022). This is a key driver for global demand for expanded shelter and essential commodities hence growth of cities and industries respectively (FAO, 2022). The same effect water availability in terms of the changed land use/cover (LULC) and industrial contribution to impacts of climate change. These changes contributes to global warming that causes evaporation increases and the most prominent increment in emission of Green House Gases (IPCC, 2007; Levermore, 2008). The declining state of water resources globally and Tanzania in particular, calls for action on how we plan and allocate the resource.

According to the 2020 UN World Water Development Report, Global water uptake has shot up by a factor of six over the past 100 years and sustains steadily at a rate of around 1% per annum owing to simultaneous growth in population, economic development and shifting consumption patterns (UNESCO, 2021; WMO, 2012). Population increase and resultant effects contributes to a fall in available water resources in Tanzania from 2700 m³ per person per year in 2001 (URT, 2018) to the current 1608 m³ per person per year as of 2015 (World Bank, 2017) and a projection of 1400 m³ by the year 2025 rises a valid alarm (URT, 2018). This is because water is an important input to all sectors of the economy and hence its deterioration will inevitably be reflected in the economy.

The World Bank hosted partnership i.e., the 2030 Water Resources Group (WRG), has undertaken a hydro-economic analysis for Tanzania and argued that, when accounting for environmental flow requirements, during dry seasons, national demand is already at 150% of accessible water (2030 WRG, 2014). Under a business-as-usual scenario and considering economic growth projections, the national water demand will increase by 216% in 2035 (2030 WRG, 2014). Government analysis estimated that overall GDP growth in 2011 was reduced from 7% to 6.4 % owing to the impacts of drought that adversely affected water and hydropower (2030 WRG, 2014). This showed that, a reduction of 0.6% of GDP corresponded to \$142 million in 2011 prices and based on average GDP per capita figures, this is equivalent to a contribution to GDP of over a quarter of a million people (2030 WRG, 2014).

Based on the global GDP, population projections, and agricultural production projections by the International Food Policy Research Institute (IFPRI), it was indicated that, there will be no water productivity gains between 2005 and 2030 (Playán & Mateos, 2006). This calls for action to study water productivity options and to implement appropriate measures.

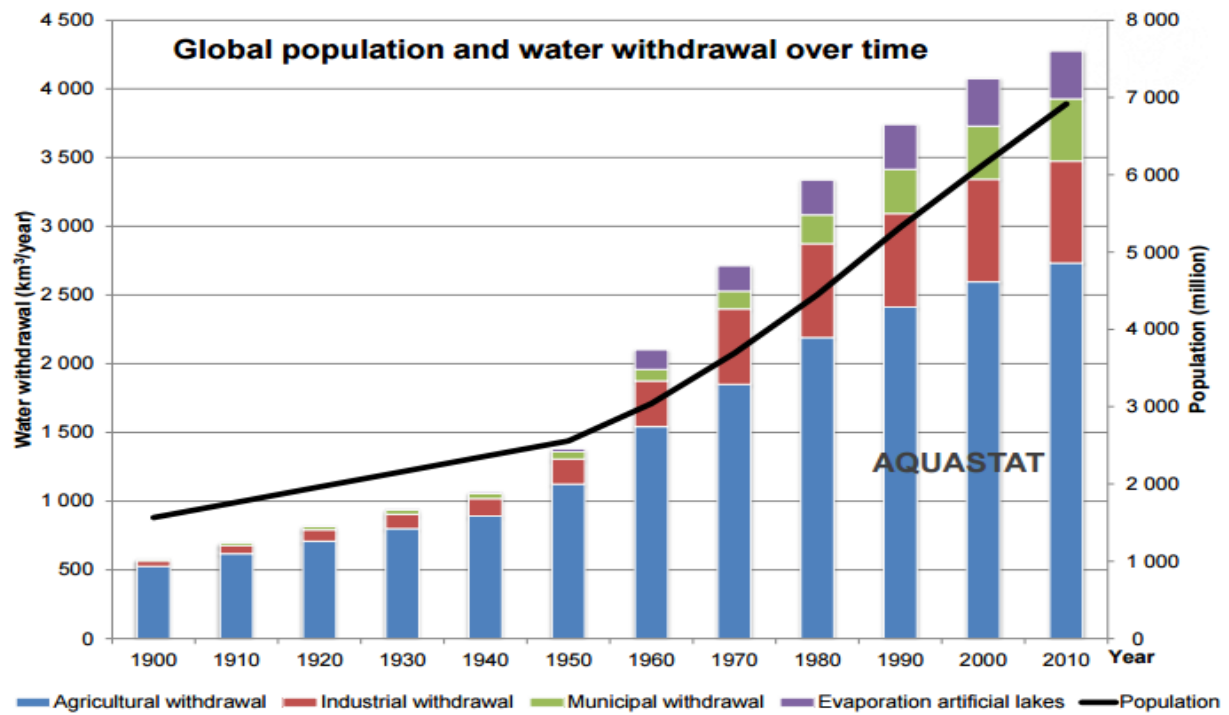


Figure 1: Sector-wise global water withdrawal and population trend which is a key driver for the changes in LULC and climate change (FAO, 2022)

2.1.3 Economic Concepts

(i) Productivity Value of Water

At the center of this study, is the assessment of PVW which is increasingly becoming a central pivot for sustainable river basin management (Mdemu *et al.*, 2013). This has been given different definitions by different authors, often according to the scale of the plant, the plot of land or watershed they were investigating, or the purpose of their study. Scholars such as Molden (1997), and Molden *et al.* (2003) define PVW as the physical mass of product or the economic value of product measured against gross inflow, net inflow, depleted water, process-depleted water, or available water. In this case, PVW is usually estimated as the amount of output produced per unit volume of water consumed. Mathematically water productivity is expressed as in Equation 1:

$$PVW (kg/m^3 \text{ or } \$/m^3) = \frac{\text{Output derived from water use (kg or \$)}}{\text{Water input (m}^3\text{)}} \quad 1$$

Increasing PVW to obtain a higher output or value for each drop of water used, is an important strategy for mitigation of water scarcity (Molden *et al.*, 2001; Watkins, 2006). Globally, projections shows that increases in PVW and growth of irrigated farms are required to cutter for half of the future growth in global water needs for a food supply that will ensure food

security for the projected 2050 population (Tropp, 2006). Further, projected increases of PVW by 30% and 60% in rain-fed and irrigated farming, respectively are needed to meet the requirement for food security of 2000-2025 period (Cook *et al.*, 2006; Rijsberman & Molden, 2001). However, this calls for multiple actions including variety type, choice of technology, in-situ water management, land use, and inputs including labor, fertilizer, and machinery (Kijne *et al.*, 2003; Rosegrant *et al.*, 2002). Each improvement will demand more capital that investors will have to contribute to adapt against the stresses (climatic or anthropogenic) and hence affects profit, profit margins, and hence the feasibility of the proposed intervention.

(ii) Profit and Profit Margin on Water Use

To assess profit margin in sectors of the economy, the study made use of paddy as a crop practiced by most farmers in the study area. The characteristic use of inputs and natural resources coupled with the typical size of land in subsistence farming limits opportunities to optimize resources/inputs and hence record low profits or profitability which are important criteria for investment decisions that affect water demand and budget in the catchment.

These criteria are sometimes used loosely but they are fundamentally different phenomena although closely related and mutually interdependent (Lusambo *et al.*, 2021). They differ in that, profits denote excess in revenue after operational/investment expenses are accounted for and are expressed as an absolute gain from an investment (Ogbadu, 2009; Stierwald, 2010). On the other hand, profitability is defined as the measure by which an undertaking makes a profit and is expressed as a percentage or ratio of profit to revenue (Eriotis *et al.*, 2011; Özçelik, 2015). It measures how efficient is an investment in using its inputs to produce profit (Niresh & Thirunavukkarasu, 2014). The need to figure out the profitability of an investment arises because, it is possible for it to generate profit but remain unprofitable which means profit is an important but inadequate indicator for a business's success (Kiganda, 2014).

The assessment of profitability of paddy farming systems in Kilombero River Catchment (KRC), adopted two commonly used approaches i.e., return on investment (ROI) and gross profit margins (GPM) also referred to as gross margins. On one hand, ROI evaluates the amount of return on an investment, relative to its cost (Botchkarev *et al.*, 2011). On the other hand, GPM measures the financial responsiveness of an investment by matching the size of profit made vs revenue generated (Eriotis *et al.*, 2011; Nariswari & Nugraha, 2020; Özçelik, 2015). The evaluation of ROI and GMP, entails a ratio between the investment's net profit to

its outlay and revenue, respectively (Botchkarev *et al.*, 2011; Eriotis *et al.*, 2011; Nariswari & Nugraha, 2020; Özçelik, 2015).

2.2 Assessment of Water Uses

2.2.1 Land Use and Land Cover Changes

Global agricultural land and human shelter have grown proportionately in the recent past. This accompanied a large increases in energy, water, and fertilizer consumption, together with substantial losses of biodiversity (Foley *et al.*, 2005; Khan *et al.*, 2019). These kinds of changes in land have enabled humans to appropriate an increasing share of the planet's resources (including water), but they also undermine the capacity of ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality, and ameliorate infectious diseases (Foley *et al.*, 2005). In this regard, Land-use/Land-cover (LULC) analysis has been considered to study the spatial and temporal trend of different sectors of economy in the study area.

The Land-use (LU) and Land cover (LC) change is a hybrid phenomenon. While on one hand LU represents human employment of the land for a number of socio economic activities, the LC connotes the physical and biotic character of the land surface as observed naturally or after alteration following the human activities (Liu, 2018; Liu *et al.*, 2005; Meyer & Turner, 1992). The LULC change causes a number of effects manifested in the biodiversity (Lupo *et al.*, 2001; Mbungu & Kashaigili, 2017). Continuous from the previous and in the coming years LULC dynamics has been playing a critical role of driving force in alteration of the global environment (Mbungu & Kashaigili, 2017).

In many parts of Africa including Tanzania, different researchers have studied and hence indicated a declining state of natural vegetation, which is replaced by altered LULC following human socioeconomic undertakings. Future projections show that, LULC changes will have even more role in the alteration of the regional hydrologic conditions that will results in a variety of impacts on ecosystem functions (Li *et al.*, 2007; Näschen *et al.*, 2018). The LULC thus presents us with a valid dilemma. On one hand, many LULC practices are essential for human existence, because they provide critical natural resources and ecosystem services, such as food, fiber, shelter, and freshwater. On the other hand, some forms of LULC play a role in the degradation of the ecosystems and services upon which humankind depend upon for their very survival.

Common understanding of the causes of LULC change is dominated by more simplifications which, in turn, underlie many ineffective environment-development policies (Lambin *et al.*, 2001). In this regard therefore, understanding the trend of LULC change provides a good starting point to address the aftermath of these changes. Kilombero River Catchment (KRC) as is the case for many other parts of Tanzania, is inadequately gauged to assist in determining the impacts of LULC change over time (Munishi-Kongo, 2013; Tumbo & Hughes, 2015). The current study has made use of the remote sensing (RS) and geographic information system (GIS) to understand the historical and project LULC change in the KRC.

2.2.2 The LULC Analysis Tools in Use

The RS techniques have been in use from about half a century ago since earlier 70's by employing optical and thermal sensors mounted in moving objects such as boats, aircraft, and satellites to provide both spatial and temporal information needed to monitor changes on earth's surface (Cetin *et al.*, 2021; Ritchie *et al.*, 2003). The GIS on the other hand, refers to systems that are used to store, retrieve, analyze and display data that are represented spatially or geographically (Goodchild, 2018). Integration of RS, GIS and global positioning system (GPS) technologies creates necessary platform around which monitoring and assessment of earth's surfaces is made possible (Goodchild, 2018; Lü *et al.*, 2019). The RS data are usually ideal to create a permanent geographically referenced database to provide a baseline for future comparisons. The integrated use of RS, GPS, and GIS data enables scholars and practitioners to develop management plans and scenarios for a variety of natural resource management applications (Lü *et al.*, 2019).

2.2.3 Selected reflections of LULC impacts in Tanzania

With the hindsight of how and the extent to which LULC change have impacted important catchments such as the Great Ruaha River Catchment where dry season flow has been impaired to the detriment of farming, tourism and HEP production (Buck & Milder, 2012; Chilagane *et al.*, 2020; Milder *et al.*, 2013; Mutayoba *et al.*, 2018), the Wami-Ruvu River catchment where the supply of water to the commercial city of Dar es Salaam has been severely impacted (Mutayoba *et al.*, 2018; Twisa *et al.*, 2020; Twisa & Buchroithner, 2019) and others, it is imperative to study critical catchments such as the KRC which makes more than 62% of the Rufiji Basin water flows to the Indian ocean (WREM & RBWB, 2013b, 2013a). In addition, the KRC feeds the 2000 MW hydro-electric production (HEP) plant i.e., the Nyerere HEP formally known as Siegler's Gorge (Dye & Hartmann, 2017), and the largest east African

mangrove forest and a mix of iconic ecosystems in between (Ajonina *et al.*, 2008; Mangora *et al.*, 2016; Monga *et al.*, 2018). Establishing a founded understanding of the historical, the current and the future trends of LULC change creates a solid foundation on which development objectives and constraints can be pegged.

2.3 Hydrologic and Hydro-Economic Modelling

Water in its natural state tends to flow, evaporate, and seep as it moves through the different components of the hydrologic cycle. Its different states within this cycle presents challenges in identifying and measuring specific units of the resource through the different components of the hydrologic cycle. Primarily because of this attribute, water is what economists call a “high-exclusion cost” resources, indicating that the exclusive property rights which are basis of a market or exchange economy are relatively difficult and expensive to establish and enforce (Young & Loomis, 2014).

To develop a thorough account of the water flow regime, its resultant benefits, impacts and the economy generated or denied, one must run catchment wide representation of hydrology and sectors of economy. To understand this, the current study has run hydrologic and hydro-economic modeling as illustrated in Chapter 3 and substantiated in subsequent sub sections.

2.3.1 Hydrologic Modeling

Global hydrological models (GHMs) have become a separate research field in the recent past/decades. Sood and Smakhtin (2015) have reviewed and made comparisons on twelve known global modelling efforts since 1989, the year the first GHM surfaced in the scientific world. The review focuses on comparing the structure, strengths and weaknesses of individual models and the objectives of model development and their initial applications. Issues such as model uncertainty, data scarcity, integration with remote sensing data and spatial resolution have also been discussed by Sood and Smakhtin (2015). This comparison efforts assisted in creating sufficient attention to the understanding of the responses to the manifestation of climate change on hydrology. All this leads to the notion of the “global water system” in which the global water flow is connected to other systems through physical relationships, economics and institutions (Alcamo, 2009; Alcamo *et al.*, 2008). This system is further complicated by the interference from humans through water storage and withdrawals (Rost *et al.*, 2008).

Models that provided early attempts to simulate global hydrology and respective processes are similar to other stand-alone hydrological models and to components of the general circulation

models (GCMs) (Sood & Smakhtin, 2015). However, they are unique in the level of detail in description of hydrologic processes, parameter estimation approaches, resolution of time and space (Haddeland *et al.*, 2011). The stand-alone models explained above are usually applied at more specific localities e.g., hydrologic basin and have several parameters that need calibration or estimated regionally. Some of the examples of these stand-alone models include the Soil and Water Assessment Tool (SWAT) (Neitsch *et al.*, 2011), the Hydrological Simulation Program Fortran (HSPF) (Bicknell *et al.*, 1997) and the Hydrologiska Byråns Vattenbalansavdelning (HBV) (Lindström *et al.*, 1997). The focus of this study was to take advantage of the robustness of the available catchment-based models to understand hydrological dynamics. This helped to relate the spatial and temporal changes of the sectors of economy to the river discharge at the outlet gauge station. The SWAT is considered to be the most robust though data heavy model but performs very well to represent hydrologic processes at catchment scale (Shope *et al.*, 2014).

2.3.2 The SWAT Model Summary

The SWAT is a comprehensive, semi-distributed river basin model that requires a large number of input parameters, which complicates model parameterization and calibration (Arnold *et al.*, 2012). It operates on a daily time step and is designed to predict the impact of land use and management on water, sediment, and agricultural chemical yields in ungauged watersheds. The model make use of data that are distributed in space such as topography, soils, land cover, land management, and weather to predict water, sediment, nutrient, pesticide, and fecal bacteria yields (Douglas-Mankin *et al.*, 2010). In the current versions, a modeled watershed is divided spatially into sub-watersheds using digital elevation data according to the density specified by the user. Sub-watersheds are further subdivided into lumped, non-spatial hydrologic response units (HRUs) consisting of all areas within the sub-watershed having similar landscape characteristics. Versions 2000 and earlier models assumed sub-watersheds as having uniform slope and climatic conditions, and HRUs as having similar soil, land use, and land management characteristics. Versions 2005 and 2009 allow slope to be included at the HRU level (Douglas-Mankin *et al.*, 2010).

The SWAT model includes sub-basin, reservoir, and channel routing components which enable the model users to obtain a better understanding of the overall hydrologic processes (e.g., baseflow ratios, ET, sediment sources and sinks, crop yields, and nutrient balances) and parameter sensitivity. In this case, the model is a near-real representation of the actual processes in the field that require constant updating and calibration. When calibrating a physically based

model like SWAT, it is important to remember that all model input parameters must be kept within a realistic uncertainty range, and which reflects the fact that no automatic procedure can substitute for actual physical knowledge of the watershed. This reiterates the need for proper calibration and validation most of which are performed either at the daily, monthly, or annual scale (Arnold *et al.*, 2012). Scholars such as Moriasi *et al.* (2007, 2012) recommend using multiple statistics and criteria in assessing model performance. Commonly used performance criterion includes the coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and percent bias (PBIAS). These statistics provide insight regarding model performance in simulating streamflow, sediment load, N, P loads, *E. coli* and fecal coliform bacteria loads across a wide spectrum of watershed conditions.

2.3.3 Hydro-Economic Modeling

The integration of the kindred economic, hydrologic and engineering processes in decision support systems for water resources management is increasingly gaining popularity (Barthel *et al.*, 2012; Sherafatpour *et al.*, 2019). The integration of economic/productive objectives and environmental stressors into unified model applications (mostly known as hydro-economic model) creates a holistic and coherent platform of the catchment problems (Alamanos *et al.*, 2020). Hence, Hydro-Economic Models (HEMs) are gaining usefulness, in water resources management, agricultural issues, policymaking, and other fields with several magnitudes, such as climate change, projects and planning etc. (Blanco-Gutiérrez *et al.*, 2013; Nakic, 2017).

The main issue in the development of an HEM is the reasonable description of the catchment system, and for this, sufficient and necessary data is required. Description of the main components of the model and their interaction is a daunting task that requires a deep understanding of catchment dynamics. This will need, at a minimum, data related to the hydrology, infrastructures, economy, supply and demand operations (Nakic, 2017). Researched baseline of the above components may be rich, but the understanding of the combined simulation is poor, since the experience is narrow, and case-specific factors are the main drivers affecting the models' structure (Alamanos *et al.*, 2020). Interdisciplinary models have been created to overcome the above issues (Alamanos *et al.*, 2020). These areas restrict the HEM's applicability in rural areas, which usually need such tools and the involvement of various disciplines and stakeholders.

Scientific deliberations and decisions are limited in respect of optimum way to address these issues (Alamanos *et al.*, 2019). Comparative studies of HEMs have been carried out using

efficiency criteria (Krause *et al.*, 2005). For example, Harou *et al.* (2009) described the status of HEMs and their prospects; Cornelissen *et al.* (2013) and Alamanos *et al.* (2020) assessed the applicability of these model types for simulating scenarios of future discharge behavior in the context of climate, LULC change and hydro-economic simulations. In addition, Bekchanov *et al.* (2015) provided a review of HEM's components and applications. In sub-Saharan Africa and Tanzania in particular, there is plenty of experiences on hydrologic models, but limited to no attempt on combine catchment hydrology and economy as a tool for water allocation. This includes: WREM and RBWB (2013b) who conducted the basin wide IWRMD Plan and Smith (2016) who carried out Kilombero specific e-flow. The same was also conducted in the Pangani basin (King & Brown, 2010), the Great Ruaha river catchment (Kashaigili *et al.*, 2007), the Mara river catchment by Tamatamah (2009) and elsewhere around the world as documented by Tharme (2003).

The present study attempts to give insights into the most appropriate way to build a HEM, better exploit the available data depending on the desirable outputs and discuss the most efficient hydroeconomic trade-off for water resources allocation. The HEM uses Kilombero river catchment as a case in point but can be replicated at scale across the river and lake basins of Tanzania and sub-Saharan Africa in general where data and knowledge is limited. The study builds on the knowledge developed elsewhere as stated above on HEM and Tanzania specific attempts discussed in Section 1.2. In this regard, the current research uses a Standard Computable General Equilibrium (CGE) Model to assess efficiency of hydroeconomic trade-offs presented as marginal productivity of water (MPW) i.e., a ratio of change in profit generated to that of use of water as an input of production (Lofgren *et al.*, 2002). This benefited from a compilation of a decade of data from social economic profiles in riparian district councils against water permits issued by Rufiji Basin Water Board.

2.3.4 The Standard CGE Model

The Computable General Equilibrium (CGE) models are known to be sizeable numerical models that attempts to harmonize economic theory with real economic data in the attempt to derive computational impacts of policies or shocks in the economy (Devarajan & Robinson, 2005; Lofgren *et al.*, 2002; Medina-López *et al.*, 2023). The CGE models fit economic data to a set of equations that aim to capture the structure of the economy and the behavioral response of economic sectors or agents. This provides a mechanism to simulate policy changes and trace their respective impact on key economic variables, including income and expenditure flows. A central concept in our case is that water demands are not static requirements but rather functions

where quantities of water used at different times have varying total and marginal economic values.

Several hydroeconomic models are in use to describe a relational interaction between water as an input of production and output volume or value. Since the 1960s there has been a changing historical nomenclature of this concept. Early use of economic water demand curves to optimize water resources systems was made by Bear *et al.* (1968) and Rogers and Smith (1970). Furthermore, Noel *et al.* (1980) studied the early description of the conceptual framework for regional-scale IWRM models where water is allocated and managed to maximize net benefits derived from economic water demand. Since then researchers have used different names to refer to applications and extensions of this hydrologic economic water modeling approach for example those who referred to it as hydrologic economic (Gisser & Mercado, 1972), hydroeconomic (Noel & Howitt, 1982), economic–hydrologic–agronomic (Lefkoff & Gorelick, 1990), integrated hydrologic–economic–institutional (Booker, 1995), integrated river basin optimization (Ward & Lynch, 1996), efficient allocation (Diaz *et al.*, 1992), integrated economic–hydrologic (Rosegrant *et al.*, 2000), economic-engineering (Lund *et al.*, 2006), integrated hydrologic–agronomic– economic (Cai *et al.*, 2003), demand and supply (Griffin, n.d.), integrated hydrologic–economic (Pulido-Velázquez *et al.*, 2006), holistic water resources–economic (Cai, 2008), integrated hydrodynamic– economic (Jonkman *et al.*, 2008), and integrated ecological–economic (Volk *et al.*, 2008).

This work uses “hydroeconomic” model and in particular employs the CGE model that has itself long been researched and used elsewhere (Noel & Howitt, 1982). This was also guided by a bibliometric study by Wei and Aaheim (2023) who analysed 97 publications by utilizing CGE models to understand climate change adaptation. This review highlighted the flexibility of CGE models in explaining both sectoral and regional impacts, together with their advanced capability to track the temporal evolution of critical economic variables. In addition, the adopted CGE model, while calculating the ratio of change in profits/revenue to change in water use across the assessment period, it also checks the accuracy by way of calculating the coefficient of determination R^2 and P-value (Lofgren *et al.*, 2002). This R^2 is a statistical indicator in a regression model that determines the relationship of variance in the dependent variable explained by the independent variable. In other words, R^2 shows how well the data fit the regression model. The importance of p-value lies in its ability to strike a sensitive relationship between statistical rigor and practical significance. A small p-value suggests that the observed effect is statistically meaningful, but it also prompts researchers to consider the

practical implications of the findings. In our case, we used the marginal productivity value of water to assess water allocation tradeoffs considering hydroelectric production, paddy, and sugarcane farming, and their impacts across the Kilombero river catchment.

2.4 The Foundation of the Researched Components

2.4.1 Climate Studies and Gap

The Kilombero River catchment is a vital economic hub in Tanzania and has been extensively studied for its hydro-climatic characteristics, including precipitation, temperature, evapotranspiration, and river discharge. However, knowledge gaps remain regarding:

- (i) **Limited Spatial Coverage:** Despite the increasing use of satellite and ground station information, limited spatial coverage hinders the comprehensive understanding of catchment variability (Näschen *et al.*, 2018; Tumbo & Hughes, 2015).
- (ii) **Temporal Data Gaps:** Longterm data trends are often incomplete which makes it challenging to make assessments and compelling arguments of the impacts of climate change over the span of extended periods (IPCC, 2007; Sigalla *et al.*, 2023; Urban *et al.*, 2016).
- (iii) **Land use/cover and climate interactions:** There exists a general lack of comprehensive analysis on how land use/cover changes such as deforestation and agricultural expansions. Additionally, there is also a gap in understanding the interaction of climate, LULC and river flows variables especially in ungauged catchments (Chilagane, 2017; Guo *et al.*, 2020).
- (iv) **Seasonality Patterns:** Although, several studies have looked at seasonality of hydro-climatic variables, there is still a need to understand their implications on water resources management and agricultural planning (Näschen *et al.*, 2019).

Addressing these gaps calls for improved methods of collection of data and analysis, integration of land use/cover change analysis and enhanced modelling techniques to predict future climate scenarios and their impacts on the catchment such as Kilombero (Höllermann *et al.*, 2021; Näschen *et al.*, 2019). This endeavor would support sustainable water resources management and economic development of the catchment and Tanzania at large.

2.4.2 Land Use/Cover

Information about LULC and alterations is useful for different groups of stakeholders to assess future pathways of sustainable water and land use for their current and future sustainability through preservation of their surrounding environment (Lupo *et al.*, 2001; Mbungu & Kashaigili, 2017; Thonfeld *et al.*, 2020). Evaluation results for Kilombero valley by different researcher have indicated changes but with different details. Thonfeld *et al.* (2020) showed that only a quarter of the catchment has not experienced changes. A third shows both spectral changes and land cover conversion. Changes detected were identified in two major regions, one in the west of the catchment and the other in the Kilombero floodplain. Both regions are important areas for food production and economic development in Tanzania through expansion of Southern Agricultural Growth corridor of Tanzania (SAGCOT) (Buck & Milder, 2012; Milder *et al.*, 2013).

Other scholars have indicated that, the Kilombero floodplain is a Ramsar protected area, half of which was converted to agricultural land in the past decades (Munishi & Jewitt, 2019; Senkondo *et al.*, 2019; Thonfeld *et al.*, 2020). Senkondo *et al.* (2019) further argues that, most of the study area was covered by the broadleaved deciduous forest i.e., Miombo (around 38% of the total area) followed by flooded herbaceous cover (11%) leaving urban areas and water bodies each occupying less than 1% of the total study area and the remainder to other LULC categories (Table 1). The studied LULC was meant to firstly build on the assessments carried out before and secondly prepare the data for SWAT model that investigated the implication of the interaction of climate, LULC and river flow parameters.

Table 1: The land cover classes of the Kilombero River Catchment (KRC) as captured by other scholars

N	Land-cover Classes	Area (km ²)	% Area
1	Cropland	412	1.26%
2	Herbaceous cover	3005	9.16%
3	Post-flooding cropland	2371	7.23%
4	Mosaic cropland	1425	4.35%
5	Broadleaved evergreen forest	2697	8.22%
6	Broadleaved deciduous forest	12 555	38.28%
7	Mixed leaf forest	2159	6.58%
8	Mosaic herbaceous cover	964	2.94%
9	Shrubland	2568	7.83%
10	Grassland	545	1.66%
11	Flooded tree cover	349	1.06%
12	Flooded herbaceous cover	3716	11.33%
13	Urban areas	12	0.04%
14	Water bodies	23	0.07%

Senkondo *et al.* (2019)

2.4.3 Implications of Prevailing Hydroclimatic Changes to River Discharge

The Kilombero River Catchment in Tanzania is experiencing significant hydroclimatic changes, primarily driven by climate variability, which are influencing river discharge patterns (Höllermann *et al.*, 2021; Näschen *et al.*, 2019). These changes include altered rainfall regimes, temperature increases, and shifts in the timing and intensity of seasonal rainfall (Senkondo *et al.*, 2019). As a result, the river's flow dynamics are impacted with detrimental aftermath on both increased flooding risks during heavy rainfall and drought conditions during dry spells. These fluctuations impact water availability, agriculture, and biodiversity within the catchment (Leemhuis *et al.*, 2017; Näschen *et al.*, 2019). The altered discharge patterns also challenge water resource management, demanding adaptive strategies to ensure sustainable water use, mitigate flood risks, and address the growing pressures of climate change on the river's ecosystem and local communities.

These interactions between hydro-climatic factors and river discharge are complex in nature and are shaped by several interconnected processes which include the following:

- (i) **Rainfall Patterns:** Many rivers are highly sensitive to changes in rainfall patterns. Seasonal rainfall variations, such as delayed or erratic rainfall, influence the volume of water that feeds into the river (Nijssen *et al.*, 2001). Increased rainfall intensity during the wet season can lead to higher river discharge, while irregular or reduced rainfall can result in lower discharge and drought conditions (Höllermann *et al.*, 2021; Näschen *et al.*, 2019).
- (ii) **Temperature Changes:** Rising temperatures in the catchment area affect evaporation rates and the snowmelt in highland areas, which can alter the volume of water entering the river (Näschen *et al.*, 2018; Sigalla *et al.*, 2023). Warmer temperatures can also influence the river's hydrological regime, increase evaporation and reduce water availability, especially during dry periods.
- (iii) **Flooding and Droughts:** The changing rainfall intensity and patterns contribute to the occurrence of both floods and droughts (Näschen *et al.*, 2018; Näschen *et al.*, 2019). Excessive rainfall can lead to rapid runoff, overwhelming the river's capacity and causing flooding, which is also the case in the study area. Conversely, prolonged dry spells reduce river discharge, threatening water availability for local communities and ecosystems (Höllermann *et al.*, 2021; Näschen *et al.*, 2019).

- (iv) **Land Use and Human Activity:** Land use changes, such as deforestation, agriculture, and urbanization, can alter the natural water absorption capacity of the catchment (Näschen *et al.*, 2019; Shaghude, 2006; Sigalla *et al.*, 2024). These changes can amplify the effects of hydro-climatic factors, leading to quicker runoff, erosion, and sedimentation that further disrupt the river's discharge and ecological balance.

Effective management of river hydrology requires addressing the impacts of climate change and human activity (Pahl-Wostl *et al.*, 2008). Understanding the dynamic interaction between hydro-climatic factors and river discharge is crucial for developing strategies to mitigate flooding, conserve water resources, and maintain the ecological health of the river basin (Pahl-Wostl *et al.*, 2008). These strategies are well developed if there is a better understanding of the altered rainfall, temperature shifts, and land-use changes which directly affect river discharge, influencing water availability, flood/drought risks, and the sustainability of the catchment's ecosystems and livelihoods. This is part of the gap that this study is trying to contribute into solving.

2.4.4 Catchment Hydrology and Economy

The relationship between catchment hydrology and the economy is multifaceted and essential for sustainable development (Di Baldassarre *et al.*, 2019). Water resources, in the form of reliable river discharge, are essential for agriculture, energy production, industry, tourism, and overall human well-being (Spulber & Sabbaghi, 2012). Changes in hydrology, whether due to climate variability, human activity, or natural processes, can have profound economic consequences, disrupting livelihoods, reducing productivity, and escalating costs (Cai *et al.*, 2013; Pahl-Wostl *et al.*, 2008; Schmietendorf *et al.*, 2017). Managing this relationship requires integrated water resource management, climate adaptation strategies, and investments in infrastructure to ensure economic stability and growth in the face of changing hydrological conditions (Engle *et al.*, 2011; Lubell & Edelenbos, 2013). This is true because river flow and the quality of water it carries draining across landscapes in the catchment influence various economic sectors. This relationship can be observed through several channels:

(i) Water Availability and Agriculture

River catchments are always crucial sources of water for irrigation, which supports agricultural productivity (Cai *et al.*, 2013; Hussain *et al.*, 2007; Sigalla *et al.*, 2022). When river discharge is consistent and sufficient, it ensures that crops have access to reliable water (Cai *et al.*, 2013). However, changes in hydrology, such as reduced discharge due to drought or altered rainfall

patterns, can lead to water shortages, negatively affecting crop yields, food security, and livelihoods, particularly in rural areas (Pahl-Wostl *et al.*, 2008).

On the other hand, excessive rainfall or extreme flooding within a catchment can damage agricultural lands, destroy crops, and displace farming communities (Höllermann *et al.*, 2021; Näschen *et al.*, 2019). Floods also lead to soil erosion and siltation, which can further degrade land quality and reduce agricultural productivity in the long term.

(ii) Hydropower Generation

Hydropower is a significant contributor to the economy, especially in regions where rivers provide a large proportion of electricity. The hydrological regime of a river catchment and its seasonal flows and volume determines the capacity and reliability of hydropower plants (Kichonge *et al.*, 2015; Schmietendorf *et al.*, 2017). A stable and predictable flow allows for consistent power generation, which is essential for industrial activity, energy security and overall economic growth.

Changes in rainfall patterns, temperature, and evaporation can contribute to significant disruption to river flows, that in turn affect hydropower production. Reduced discharge during dry seasons or prolonged droughts can lead to power shortages, increased energy costs, and even the need for more expensive alternative energy sources, disrupting economic activities reliant on stable energy supplies (Byers *et al.*, 2020; Hunt *et al.*, 2018).

(iii) Water Quality and Industry

Many industries such as manufacturing, mining, and textiles rely heavily on river water for processing and cooling (Gao *et al.*, 2024; Spulber & Sabbaghi, 2012). Changes in river hydrology can influence water availability and quality. Inadequate water supplies due to low river discharge, or pollution resulting from increased runoff during heavy rainfall, can hinder industrial processes and raise operational costs (Sarker *et al.*, 2021).

On the other hand, pollution and ecosystem services affect water quality which result from land-use changes (e.g., deforestation, urbanization) and industrial discharge (Sarker *et al.*, 2021). These can impair aquatic ecosystems, which provide critical services such as fisheries and tourism. Degraded water quality can increase the costs of water treatment, reduce fish stocks, and damage ecosystems, affecting industries that rely on these resources (Akhtar *et al.*, 2021).

(iv) Flooding and Economic Disruption

Flooding within river catchments is a significant concern for both developed and developing economies (Yin *et al.*, 2021). Extreme floods damage infrastructure e.g., roads, bridges, homes, and agricultural land that lead to high recovery costs, loss of property, and economic disruption (Manzoor *et al.*, 2022). For developing economies, such flooding can wipe out years of economic progress and hamper development efforts.

In areas with frequent flooding, communities may face displacement, resulting in a loss of livelihoods, particularly for those in agriculture and fishing (Manzoor *et al.*, 2022). Displacement also increases social costs, including health crises and reduced productivity, which further stunts economic growth.

(v) Tourism and Recreation

Rivers often play a central role in ecotourism, especially when their catchments are rich in biodiversity and scenic beauty (Boluk *et al.*, 2019; McDonald, 2006). The health of the river system, including its hydrology, directly impacts tourism activities like fishing, boating, and wildlife viewing (McDonald, 2006). Changes in river flow and water quality can reduce the appeal of these destinations, impacting local economies dependent on tourism.

Rivers provide water for recreational activities such as swimming, fishing, and rafting, which contribute to local economies (Meo *et al.*, 2020). Hydrological changes such as reduced flow or pollution can diminish these recreational opportunities, leading to a loss of income for communities that rely on these industries.

(vi) Urbanization and Water Supply

The hydrology of river catchment is closely linked to urban development. Cities depend on rivers for drinking water, waste disposal, and storm water management (Bao & Fang, 2012). As urban populations grow, the demand for water increases, and the river's ability to supply this water becomes crucial (Mbonaga *et al.*, 2024). Over-extraction or pollution can degrade water quality and affect the reliability of water supply, which in turn can reduce productivity in urban areas and raise the costs of water management.

Climate change exacerbates challenges related to urbanization, such as flooding and water scarcity. Changes in rainfall patterns and increased extreme weather events affect both the availability and quality of water, making it harder to maintain reliable urban water systems.

(vii) Fisheries and Biodiversity

For regions where fisheries are a key economic activity, changes in river hydrology can directly affect fish populations (Ghose, 2014). Reduced river flow can decrease fish spawning areas, while floods can disrupt aquatic habitats. Overfishing or water pollution further compounds these problems, leading to a decline in fish stocks and impacting the livelihoods of local fishing communities (Chakraborty, 2021).

Healthy river ecosystems support biodiversity, which contributes to ecosystem services like soil fertility, water purification, and flood regulation (Chakraborty, 2021). Disruptions in river hydrology, whether through over-extraction, pollution, or climate change can reduce biodiversity, affecting all industries that rely on these services.

(viii) Climate Change and Long-Term Economic Viability

Climate change leads to greater unpredictability in river catchment hydrology, with more frequent and intense weather extremes like floods and droughts (Hallegatte *et al.*, 2011). This unpredictability poses risks to economies, especially in sectors such as agriculture, hydropower, water supply, and tourism (Tol, 2018). Economies reliant on steady river flows face long-term challenges in managing water resources, maintaining infrastructure, and protecting livelihoods.

Adaptation to these changes requires investment in infrastructure, policy reform, and technology to manage water resources more efficiently (2030 Water Resource Group [WRG], 2014). The cost of inaction can be significant, with long-term disruptions to economic growth, infrastructure, and public health.

2.5 Importance of Kilombero Catchment

Kilombero River Catchment (KRC) is central to major economic expansion programs under the southern agricultural growth corridor of Tanzania (SAGCOT) and constitutes one of its six clusters namely; Rufiji, Kilombero, Ihemi, Mbarali, Ludewa and Sumbawanga. It forms part of the most productive and ecologically important wetlands in Tanzania i.e., the Kibasila wetland. The Kilombero floodplain supports several large-scale investors who are already engaging smallholders in a model connecting investors as a nucleus without-grower schemes for sugar, rice and teak production. The backbone road and power infrastructure reach as far as Ifakara, the major population center, and the Tanzania-Zambia railway authority (TAZARA)

railway passes close by many of the communities and farms in the corridor. However, the last-mile infrastructure in the cluster is considerably poor causing a limits market access for smallholders and new investors. The same elevates transportation costs and inhibits the transfer of knowledge and agricultural inputs to farmers.

The Kilombero floodplain which is center for most economic activities in the study area is becoming progressively more degraded in recent years due to an influx of crop producers and grazers (Kangalawe & Liwenga, 2005). There is inadequate enforcement capacity to tackle these conflicts which is to the detriment of wildlife, fisheries, and human livelihoods. In the same vein, the growth of smallholder farming (and to a lesser extent commercial farming) has interfered with several key wildlife corridors that once linked the Udzungwa Mountains to the Kilombero floodplain and Selous Game Reserve currently referred to as the Nyerere National Park (Mtega, 2017). It is inevitable that, in the course of time, such changes are expected to increase levels of human - wildlife conflict while reducing game populations in the Nyerere and Udzungwa protected areas. The Kilombero Valley has excellent soils supporting a variety of agricultural uses. This is attributed to reasons for majority of the population (85% to 90% in some administrative jurisdictions), engaging in agriculture.

Other economic activities are small-scale businesses and elementary occupations but all are based directly or indirectly on exploitation of natural resources (Kangalawe & Liwenga, 2005; Mtega, 2017). Similar to this was a study by the current authors who also found out that farming dominates livelihood activities in the study area (at 71%) followed by Small-Scale Businesses (21%), Livestock Keeping (4%) and Handcrafts especially weaving and mechanics (4%) (Sigalla *et al.*, 2022). It was further noted that farming is predominantly Paddy (82%), Sugarcane (10%) and Mixed Paddy and Maize (8%). Other crops were deemed insignificant both in terms of water use and the size of farms (e.g., bananas and vegetables). Singling paddy, it was further noted that, under small holder schemes there are four main farming practices viz. rainfed conventional transplant and flooding system: The CTFS (48%), irrigated CTFS (29%), rainfed system of rice intensification (SRI) (14%) and irrigated (SRI) (9%) (Sigalla *et al.*, 2022).

CHAPTER THREE

MATERIALS AND METHODS

3.1 The Study Area

3.1.1 Location and Summary of Key Attributes

The current assessment focused within the hydrologic boundaries of the Kilombero River Catchment (KRC) (Fig. 2). This is part of Tanzania's largest hydrologic basin i.e., the Rufiji River Basin (RRB) which is spread across the 177 420 km² (about 20% of Tanzania). The KRC in particular extends between Longitudes 34°00'E - 37°20'E and Latitudes 07°40'S - 10°00'S and covers an area of approximately 40 000 km² (WREM & RBWB, 2013a). The cross section of the catchment is characteristic of a graben structure with Udzungwa mountain ranges and Mbarika escarpments forming the northly and southerly crests respectively while the middle part (the flood plain) forming the trough extending around 1967 km² (Kato, 2007; Mombo *et al.*, 2011). This middle portion of the catchment constitutes one of the largest wetlands in east Africa i.e., Kibasira wetland which is at around 300 m above mean sea level (Kangalawe & Liwenga, 2005) and most of its area is internationally designated as a Ramsar site for its environmental significance (Wilson *et al.*, 2017). The KRC is the most important catchment in respect of agriculture development potential, energy production, natural resources and flow to RRB (Wilson *et al.*, 2017). Tributaries that form the Kilombero River are Lumemo, Luipa, Mngeta, Kihansi, Mpanga, Mnyela, Ruhuji and Furuu. Most areas of KRC are situated in the administrative region of Morogoro where its most developed center (Ifakara) is found some 230 km from Morogoro town or 400 km from Dar es Salaam, the commercial City of the country.

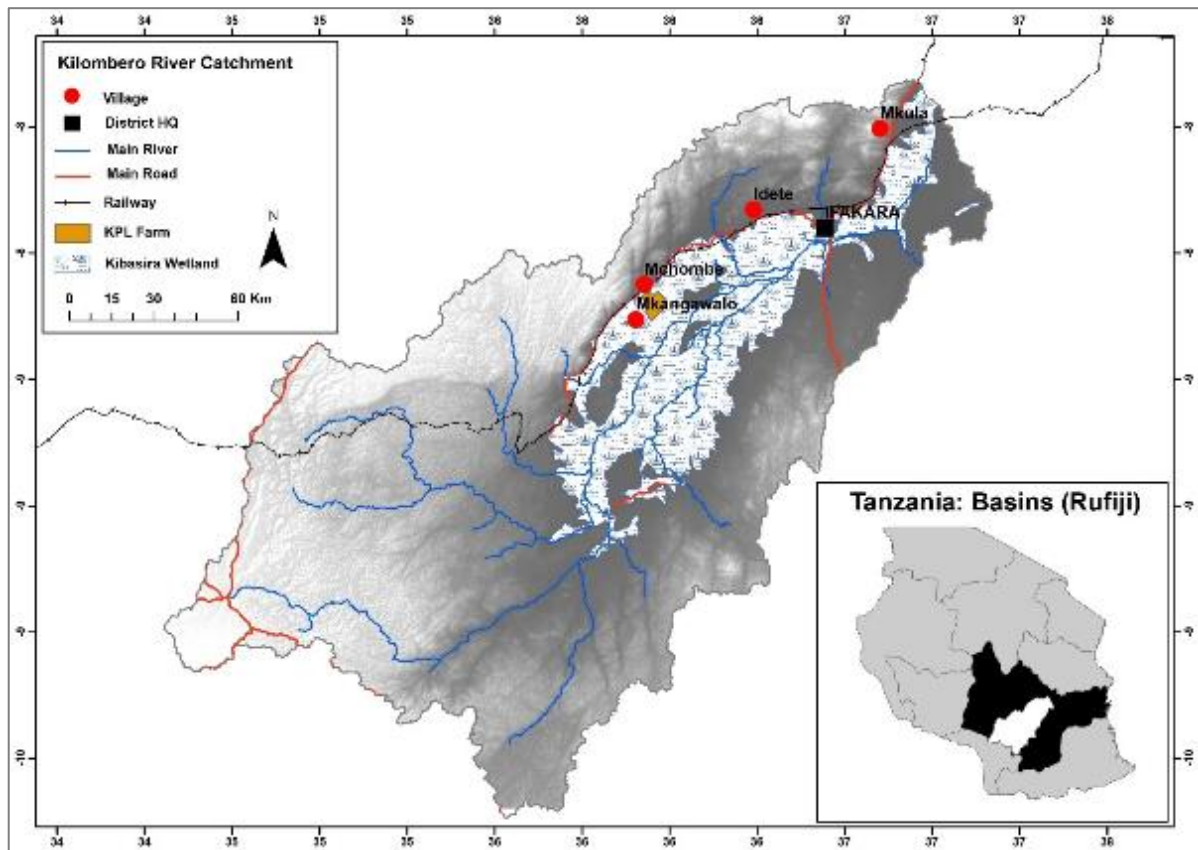


Figure 2: Map of the Kilombero River Catchment showing the major hydrologic and geomorphologic features

3.1.2 Climate Characteristics of Kilombero River Catchment

The climate conditions in the Kilombero catchment is highly variable in comparison between the highlands and the lowlands with mean annual precipitation varying from 1100 mm to 2100 mm (Koutsouris *et al.*, 2016; Näschen *et al.*, 2018; Wilson *et al.*, 2017). The highest received rainfall in history (1500 – 2100 mm) falls in eastern Mahenge and Central Udzungwa Mountains (which are drained by the Mpanga and Kihansi Rivers) and the low altitude southwest plains (Koutsouris *et al.*, 2016; Näschen *et al.*, 2018). The lower - lying valley plains of Kilombero receive about 1200 to 1400 mm of rain per year. The largest part of annual rainfall (80-90%) falls during the rainy season occurring between December and April, while the period ranging from June to September is fairly dry with typical monthly amounts below 10 mm, except in the Udzungwa Mountains (Koutsouris *et al.*, 2016; Näschen *et al.*, 2018).

While the Kilombero valley experiences a warmer climate with an annual mean daily temperature of 24°C at Ifakara, the mountainous areas are cooler with an annual mean daily temperature of 17°C. December and January are the warmest months with day temperature in the upwards of 27°C in the valley and 19°C in the mountains (Koutsouris *et al.*, 2016; Näschen *et al.*, 2018). July is the coolest month with temperatures around 21°C and 14°C in the lowlands

and highlands, respectively. Other climatic variables experience similar spatial variation. Relative humidity changes spatially as well from 58 to 85% (with an average of 75%) in the Kilombero valley and from 70 to 87% (with an average of 80%) in the Udzungwa Mountains (Koutsouris *et al.*, 2016; Näschen *et al.*, 2018; Wilson *et al.*, 2017). Annual potential evaporation in the Kilombero is estimated at 1800 mm per year. There are trends indicating increasing temperatures and changing precipitation patterns that are expected to cause increased evapotranspiration, reduced runoff and reduced groundwater recharge (WREM & RBWB, 2013b) which will impact water availability and economy of KRB.

3.1.3 Hydrology of Kilombero River Catchment

The river networks in Kilombero catchment start from the Udzungwa Mountains on the western rift and the Mahenge Mountains on the eastern rift. There are three main rivers namely Ruhudji, Mnyera and Mpanga that converge in the Kilombero river. Furuu is the main tributary from the east, while Kihansi, Ruipa, Lumemo and Msolwa are the main tributaries on the western bank. Kibasila wetland/swamp is one of the few natural lakes in the valley followed by the Kihansi Reservoir which was made for hydropower after damming the river in 90s (Zilihona *et al.*, 1998). Although the area of KRC represents only about 20% of the entire Rufiji River Basin (RRB), the catchment contributes about 62% of the total annual average water flow of 13.8 Bm³/yr as summarized in Table 2 (Mwalyosi, 1990; WREM & RBWB, 2013b). Attributes of different catchments in the Rufiji River Basin indicating Kilombero river to be the highest contributor of flow although its second largest catchment of the four (Table 2).

At mountains and relative to the flat floodplain, the aquifers are small, weathered and fractured basement aquifers with low to medium groundwater potential. The higher groundwater yield potentials are found in aquifers within the alluvial sedimentary sequence, especially in the center of the Kilombero valley (Burghof *et al.*, 2018; Senkondo *et al.*, 2017). Owing to the sediments, the aquifers in the valley bottom are in general shallow (Burghof *et al.*, 2018; Senkondo *et al.*, 2017). The recharge of aquifers comes mostly from rainwater infiltration and to a limited extent from rivers and lakes. The analysis by Rufiji Basin Water Office showed that the water table levels and precipitation are highly correlated (RBWO, 2010).

Table 2: Attributes of different catchments in the Rufiji River Basin

No	Catchment	Area (Km ²)	% of Area	Mean Annual Rainfall (mm)	Mean Annual Flow (bcm/yr)	% of Runoff
1	Great Ruaha	85 554	46.6	400 – 1200	3.3	14.8
2	Kilombero	40 430	21.9	1000- 1800	13.8	62.2
3	Luwegu	26 300	13.8	800 – 1400	4	18.0
4	Rufiji	27 160	17.7	650- 1100	11.1	5.0
5	Total	183 791	100		22.2	100

Mwalyosi (1990) and WREM and RBWB (2013b)

3.1.4 Social Economic Profile of KRC

Based on the national population and household census of 2022, KRC hosts 5 833 123 people out of which 51.3% are females and 48.7% males and is generally characterized by households composed of 4 - 5 family members (NBS, 2023). The exercise also indicated that, there was about 50% of the population under the age of 21 years while 73% were below the age of 40 years (WREM & RBWB, 2013a) signifying a good number of family workforce. Culturally communities have age groups that are linked with decision making in families including farm inheritance (Bluwstein *et al.*, 2018; Maganga *et al.*, 2016). Furthermore, there are statutory organs from village, ward, division to district level who oversee allocation of water and farms/land. Other structures include community associations related to water allocation and revolving funds and other forms of informal groupings in support of their livelihood improvements.

There is significant inequality in the catchment communities, where huge disparities in household ownerships, household services, income, and expenditure (WREM & RBWB, 2013a). About 30% of the population in rural areas and a quarter of the population in urban areas fall below the basic poverty line; which means they have an income below TZS 36 500 per month per adult (WREM & RBWB, 2013a). Kangalawe and Liwenga (2005) identified wealth groups based on size of farm owned by communities in and outside the wetland. They categorized ownership of up to 2.1 ha, 2.8 ha and above 5.5 ha of farm in wetland to be poor, medium and wealthy farmers, respectively. In addition, categories in dryland included farm size of about 0.2 ha, 0.6 ha and above 0.7 ha as poor, medium and wealthy farmers, respectively.

3.2 Description of Collected Data

3.2.1 Data Used for Hydroclimatic and Land Use/Cover Assessment

(i) Historical Hydro-Climatic Data

This research work made use of the daily observed data from Tanzania Metrological Authority (TMA) and Rufiji Basin Water Board (RBWB). To cover the missing areas and data, the study used satellite records between 1981 and 2020 for climate variables. A total of 29 gridded satellite points were used (Appendix 1 and 2). The selected satellite data were downloaded from Climate Hazards Group InfraRed Precipitation (CHIRP) for precipitation data whereas Observational-Reanalysis Hybrid (ORH) was used for T_{min} and T_{max} . The selection of these data sources were guided by validation work by previous researchers such as Dinku *et al.* (2018) and Gebrechorkos *et al.* (2018). In addition, daily river flow discharge data were obtained from an e-flow study by Smith (2016). In addition to other data, a Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a 90 m raster resolution was used to delineate the catchment.

(ii) Projected Climatic Data

Monthly temperature and precipitation projection data were obtained from the Regional Climate Models (RCMs) which is under the Coordinated Regional Climate Downscaling Experiment (CORDEX) AFR-44 domain. The data ranged from 2021 to 2050 with the resolution of 0.44° East and 0.44° North. This helped for all the three major climatic zones of Udzungwa, escarpment, Mahenge escarpment and the lower lying Kilombero valley. These satellite data were accessed from the World Climate Research Program (WCRP) website (CORDEX-DKRZ - Home | ESGF-CoG) on 23rd April 2024. More details about these data are well presented by Nikulin *et al.* (2012) and the same have also been extensively used by other scholars such as Borhara *et al.* (2020), Luhunga *et al.* (2018) and Näschen *et al.* (2019).

(iii) Data Used for Land-Use Land-Cover Assessments

The overall spatial and temporal LULC alteration for KRC was detected for four-time epochs i.e., 1991, 2001, 2011 and 2021 based on the analysis of RS Landsat imagery and GIS data of the study area. The selection of these time epochs was meant to coincide with changes in national water policies since its first promulgation in 1991. Appropriate Landsat imageries

were acquired from the United States Geological Survey (<https://earthexplorer.usgs.gov/>) i.e., a 30 m resolution, multispectral level 1 data with cloud cover less than 10% (Appendix 3).

(iv) Additional Data for SWAT Model

The SWAT framework used in this assessment was built on QGIS 2.6.1 interface, the inputs data collected to set up the model includes spatial data, hydrological data and meteorological data presented above. In addition, spatial data included 30 m resolution digital elevation model (DEM) downloaded from NASA (<https://reverb.echo.nasa.gov/>). The digital LULC map of the study area for 1991, 2001, 2011, 2021, 2031 and 2041 was adopted from the LULC change analysis for the study area as reported in Sigalla *et al.* (2024). Soil data and information on related soil properties were obtained from the Food and Agriculture Organization (FAO) soil map (FAO, 2005). Meteorological data comprised of relative humidity, solar radiation, wind speed and minimum and maximum temperature data which obtained from CFSR Global Weather Data for SWAT (<https://swat.tamu.edu/data/cfsr>) and rainfall data which obtained Tanzania Meteorological Authority (TMA) and, hydrological data included water discharge, recorded from Kilombero at Swero gauging station obtained from Rufiji Basin Water Board (RBWB).

3.2.2 Data Used for Hydro-Economic Assessments

This covers data collected for calculation of productivity value of water and hydro-economic trade-offs across the main sectors of economy. In this case the study collected water use data from Rufiji Basin Water Board (RBWB) and respective users such as Kilombero Sugar Company Ltd (KSCL), Kilombero Plantations Ltd (KPL) and Tanzania Electricity Supply Company (TANESCO). In addition, the data for other inputs of production, product output and output value were also collected from these entities. However, for smallholder farmers who characteristically don't keep data in time series, triangulation of values was adopted by mixing questionnaires responses at farms and aggregation points vs the data records at district agriculture development departments. Appendix 1 to 9 gives a summary of a decade's worth of data from the respective entities mentioned above and captured attributes summarized in Appendix 4.

As guided by TANESCO, an average of TZS 27 or USD 0.01 was adopted as cost to generate a kWh and for the consumptive use of water a value for annual evaporation for Udzungwa escarpment was calculated as reported in Sigalla *et al.* (2023). Expansion plan of hydropower generation from this catchment is adopted from power masterplan that indicated Mnyera

Kwanini (143.9 MW), Mnyera Mnyera (137.4 MW), Mnyera Pumbwe (122.9 MW), Upper Kihansi (120 MW) and Mnyera Kisingo (119.8 MW) which is over and above the current Kihansi (180 MW).

3.3 Methods

3.3.1 Methodological Approach for Assessing Climatic Pattern

(i) Preparation of Data for Analysis

Simple statistical conversions of temperature and precipitation units from kelvin (K) to centigrade ($^{\circ}\text{C}$) and $\text{kg m}^{-2} \text{s}^{-1}$ to mm were processed by using climate data operators (CDO), respectively. Each parameter was aggregated in monthly-to-yearly average time steps. The Thornthwaite method was utilized in the computation of potential evapotranspiration (PET) as discussed in Section 3.3.1(iv). Analysis of data was then performed using the statistical R packages known as climate data tools (CDT) version 8.0. The tool was developed by the International Research Institute for Climate and Society (IRI) at Columbia University and can be accessed and installed online freely through the R programming language (Dinku *et al.*, 2022). Finally, the NCAR Command Language (NCL) was used to generate figures from processed data based on their variable needed.

(ii) Spatial Interpolation of Hydro-Climatic Variables

The spatial interpolation approaches and tools have been applied in many disciplines. There are dozens of interpolation methods but frequently used ones includes Inverse distance weighting (IDW), ordinary kriging (OK), and ordinary co-kriging (OCK) (Achilleos, 2011; Li & Heap, 2011; Mueller *et al.*, 2004). Data variation is a main impact factor and has momentous effects on the performance of the methods. As the alteration increases, the accuracy of all methods decreases and the magnitude of decrease is method dependent (Li & Heap, 2011). According to these scholars, IDW approach produced the best performances based on its performance against mean error (ME), mean absolute error (MAE), mean squared error (MSE) and root mean squared error (RMSE) that were used by Li and Heap (2011). On these bases, the IDW method was chosen in the current study. The approach entail an interpolation that estimates cell values by averaging the values of sample data points in the neighborhood of each processing cell (Samanta *et al.*, 2012). The closer a point is to the center of the cell being estimated, the more influence, or weight, it has in the averaging process.

From the dataset illustrated in Appendix 1, a simple arithmetic mean of variables were calculated to represent Udzungwa escarpment (NE to NW stretch), the lower lying plain in the middle part of the catchment (Kilombero Valley), Mahenge escarpment (SE to SW stretch) and the mean for entire catchment. This was based on the spatial analysis which agreed well with other studies that both showed that, the study area experiences different climatic conditions in the lower and higher lying terrains (Näschen *et al.*, 2018; Sigalla *et al.*, 2023). The spatial analysis was performed under ArcMap 10.5 software within its spatial analysis function tool. This performed kriging by Inverse Distance Weighted (IDW) Interpolation as discussed in Achilleos (2011) and Mueller *et al.* (2004). In this methodology the estimation of the value z at location x is a weighted mean of nearby observations given by Equation 2:

$$z(x) = \frac{\sum_i^n W_i Z_i}{\sum_i^n W_i} \quad 2$$

Whereby, $W_i = |x - x_i|^{-\beta}$ and where $\beta \geq 0$ and corresponds to the Euclidean distance. The inverse distance power, β , determines the degree to which the nearer point(s) are preferred over more distant points. Typically, $\beta = 1$ or $\beta = 2$ corresponding to an inverse or inverse squared relationship. The number of surrounding points, n , to be included decides whether a global or local weighting is applied. Both parameters β and n may be fine-tuned by cross-validation. If point x coincides with an observation location ($x = x_i$), then the observed value, x , is returned to avoid infinite weights.

(iii) Statistical Trend Analysis for Hydro-Climatic Variables

The statistical trend estimation methods are well established and include linear curves, change-points, accelerated increases, other nonlinear behavior, and nonparametric descriptions (Mudelsee, 2019). About twelve statistical test are in use for hydroclimatic data testing (Kundzewicz, 2000). Some of these are parametric and others are non-parametric. Parametric tests assume that the time series data and the errors (deviations from the trend) conform with a particular data distribution (usually normal distribution). Parametric tests on the other hand, quantify the change in the data (e.g., size of change in the average or gradient of the trend) (Kundzewicz, 2000).

Parametric tests are generally more useful than non-parametric tests where the assumption of normally distributed data is violated, resampling analysis can be used to estimate the significance level or critical test statistic values for various significance levels. Non-parametric tests are generally distribution-free, they detect trend/change, but do not quantify the size of

the trend/change. They are very useful because most hydrologic time series data are not normally distributed (Kundzewicz, 2000). The following are the statistical test in use to detect change for hydro-climatic time series data:

- (i) Mann-Kendall (non-parametric test for trend)
- (ii) Spearman's Rho (non-parametric test for trend)
- (iii) Linear Regression (parametric test for trend)
- (iv) Distribution-Free CUSUM (non-parametric test for step jump in mean)
- (v) Cumulative Deviation (parametric test for step jump in mean)
- (vi) Worsley Likelihood Ratio (parametric test for step jump in mean)
- (vii) Rank-Sum (non-parametric test for difference in median from two data periods)
- (viii) Student's t (parametric test for difference in mean from two data periods)
- (ix) Median Crossing (non-parametric test for randomness)
- (x) Turning Points (non-parametric test for randomness)
- (xi) Rank Difference (non-parametric test for randomness)
- (xii) Autocorrelation (parametric test for randomness)

In the present case, the non-parametric Mann-Kendall (MK) statistical tests was applied with a confidence level of 95% (Chen *et al.*, 2007; Hussain & Mahmud, 2019; Khavse *et al.*, 2015; Yavuz & Erdo\u015fan, 2012). This method has been advocated by the World Meteorological Organization (WMO) as the best approach to evaluate trends in environmental data time series (Huret & Legras, 2014). The method is simple, robust against outliers and can handle missing values (Gao *et al.*, 2017). Equation 3 and 4 describes the calculations for the selected statistical test involving the key hydroclimatic parameters viz. precipitation, temperature, evaporation and river discharge. Following the results of the MK test, was the determination for acceptance of null hypothesis i.e., no monotonic trend in the series or alternative hypothesis i.e., there is positive, negative or non-null (Gao *et al.*, 2017; Huret & Legras, 2014).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad 3$$

In this relation, the sgn series is defined by Eqn. 3.4 below:

$$\text{sgn}(x) = \begin{cases} +1 & \dots \dots \text{if} \dots \dots (x_j - x_k) > 0 \\ 0 & \dots \dots \text{if} \dots \dots (x_j - x_k) = 0 \\ -1 & \dots \dots \text{if} \dots \dots (x_j - x_k) < 0 \end{cases} \quad 4$$

Whereby, S is the test statistic, x_j and x_k are the sequential variables in a series from $i=1, 2, \dots$ to $n-1$ and $j = k+1, \dots$ to n , and n is the length of the sample. If n is bigger than 8, test statistic S approximates to normal distribution. The mean of S is 0 and the variance of S can be acquired as follows:

$$\text{var}(S) = \frac{n(n-1)(2n+5)}{18} \quad 5$$

Then the test statistic Z is denoted by Eqn. **Error! Reference source not found.**

$$Z = \begin{cases} \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if} \rightarrow S > 0 \\ 0 & \dots \dots \text{if} \rightarrow S = 0 \\ \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if} \rightarrow S < 0 \end{cases} \quad 6$$

If $Z > 0$, it indicates an increasing trend, and vice versa. Given a confidence level α , the sequential data would be supposed to experience statistically significant trend if $|Z| > Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is the corresponding value of $P = \alpha/2$ following the standard normal distribution. After determination of increasing, decreasing or no trend by MK test, the magnitude of the trend was evaluated by a simple non-parametric slope estimator procedure developed by Sen (1968) as presented in Equation 7 and 8 which denotes a liner model that measures change of slope.

$$Q_i = \frac{(X_j - X_k)}{(j - k)} \text{ for all } k < j \text{ and } i = 1, \dots, N \quad 7$$

$$Q_{med} = \begin{cases} Q \left[\frac{(n+1)}{2} \right], & \text{where } N \text{ is odd} \\ Q \left(\frac{N}{2} \right) + Q \left[\frac{N+2}{2} \right], & \text{where } N \text{ is even} \end{cases} \quad 8$$

Whereby, Q_i is the slope between data points X_j and X_k , Q_{med} is median slope estimator which reflects the direction of the trend in the data.

(iv) Calculation of Potential Evapotranspiration

To run statistical tests for potential evapotranspiration (PET), it was necessary to calculate the same from the available temperature data. Basing on that, PET was calculated using Thornthwaite formula as discussed in depth by other scholars such as (Chang, 1959; Chen *et al.*, 2005; Olaiz *et al.*, 2018). The Thornthwaite equation is a method developed by Thornthwaite (1948) based on an empirical methodology in order to estimate potential evapotranspiration (Chang, 1959; Chen *et al.*, 2005; Olaiz *et al.*, 2018; Thornthwaite, 1948, 1957; Trajkovic *et al.*, 2019). It uses the empirical correlation between mean air temperature and transpiration rates, and once the basic data have been evaluated requires only knowledge of mean air temperature. It does not suffer regionalization issues which is the case for other methods such Penman-Monteith whose constants are empirical and vary from place to place (Chang, 1959; Nikam *et al.*, 2014).

Thornthwaite is relatively simple to compute, as it can be reduced to the reading of a nomogram and can be used daily. On the other hand, one of the commonly used and very accurate evaporation estimator: The Penman-Monteith method is based on a partly empirical reconciliation of aerodynamic and heat-balance approaches and requires a knowledge of mean air temperature, relative humidity, sunshine hours, and wind miles. The computations are more involving and requires many variables compared to Thornthwaite's which becomes more attractive in data scarce context facing Africa and Tanzania is no exception. The guiding equation for Thornthwaite approach is summarized in Equation 9 to 12:

$$E_T = 16L_a \left(\frac{10T}{I_t} \right)^a \quad 9$$

$$I = \sum_1^{12} i_n \quad 10$$

$$i = \left(\frac{T_n}{5} \right)^{1.514} \quad 11$$

$$a = 6.75 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.49239 \quad 12$$

Whereby, ET is the monthly PET (cm); T is the mean monthly air temp ($^{\circ}\text{C}$); I is annual heat index in particular year which is taken as summation of monthly heat index values i ; L is average day length (hrs) of the month being calculated.

(v) Quality Assurance for Hydroclimatic Time Series Data

To have better spatial coverage of the study area, it was opted for hydroclimatic data sources such as historical or projected satellite data. These type of sources may have limitation born out of cloud cover, atmospheric interference, instrument resolution, temporal limitation related to satellite revisiting same area and data access costs (Al-Wassai & Kalyankar, 2013; Loew *et al.*, 2013). To address these challenges, temperature and precipitation data were downloaded from satellite sources that have been validated to be accurate in this part of Africa i.e., CHIRPS and ORH for precipitation and temperature respectively as validated by Dinku *et al.* (2018) and Gebrechorkos *et al.* (2018). On the other hand, the projected river discharge data were obtained from an e-flow study by Smit (2016).

3.3.2 Methodological Approach for Assessment of Land Use/Cover Change

(i) Image Pre-Processing and Classification

The satellite images were geometrically rectified to ensure geometric compatibility and registered to the UTM map coordinate system UTM zone 37 South, Spheroid Clarke 1880, Datum Arc 1960. Image mosaic was conducted to combine images of the same year with same path and different row to create a single image that covers the entire clusters. The unsupervised image classification was carried out for all images using ERDAS IMAGINE. A maximum of thirty-six (36) LULC classes were formulated. The formulated classes were visually interpreted and validated using ground truthing data and hybrid google maps. Similar classes were joined and recorded into general classes based on the classification scheme established during ground truthing (Appendix 5).

(ii) Accuracy Assessment

Kappa coefficient statistics were used to assess the accuracy of final classified image (Equation 13). Reference images for accuracy assessment were developed based on ground truthing data.

$$K = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} \times x_{+i})} \quad 13$$

Whereby, N is the total number of sites in the matrix, r is the number of rows in the matrix, x_{ii} is the number in row i and column i , x_{+i} is the total for row i , and x_{i+} is the total for column.

(iii) Change Detection Analysis

Change detection analysis was carried out to establish, extent, rate and spatial changes in LULC between different time epochs. The study used post-classification comparisons to assess land-use and land-cover changes. The approach identifies changes by comparing independently classified multi-date images pixel by pixel using a change-detection matrix (Kashaigili *et al.*, 2006). The estimation for the rate of change for the different land covers was computed based on Kashaigili and Majaliwa (2010).

(iv) Predicting Future Land Use/Cover Change

Classified land use land cover map for 2011 which represents the historical and 2021 which represent current were used to generate conditional transition probabilities (Appendix 6) which later used simulate land use land cover for the 2031 and 2041. Markov chain is a statistical tool that explained the probability of LULC from one time period to another by developing a transitional probability matrix between initial period and second period based on the spatial neighborhood effects (Al-Bakri *et al.*, 2013; Yikalo & Pedro, 2010; Wang *et al.*, 2004). Spatial neighborhood effect is the state of neighboring cells to influence the transition of a given cell into different states (Chilagane *et al.*, 2020). This model was based on using and evaluating LULC layers of previous years to predicting the spatial distribution of land uses in the future (Wu & Silva, 2010). For better simulation of data patterns of land use changes in quantity and space, the combination of two techniques Markov chain analysis and Cellular automata (CA-Markov) were used.

(v) The CA-Markov Model Setup and Validation

The simulated model was developed by using IDRISI Selva v.17.0 software (Rutherford *et al.*, 2015). In the developing CA Markov model, the classified land use map of 2011 which represents past, and 2021 which represent present time developed in QGIS 2.12.1 were converted into IDRISI data format and selected to be input data into the model, to calculate matrices of conversion probabilities and conversion areas (Transition area matrix and transition probability matrix). For model validation the simulated land use/cover map for 2021 was compared with the actual satellite derived land use/cover map based on the Kappa statistics. Then, standard Kappa index was used to check whether the model is valid or not (usually the Kappa Index for a valid model is >70%) (Wen, 2008). If the model has the Kappa Index less than 70% then the suitability map for the land covers and filter used should be repeated based on several considerations.

3.3.3 Methodological Approach for Hydroclimatic Limitation of Sectoral Water Uses

The parameters assessed above were meant to contribute to determination of hydrologic carrying capacity of Kilombero river catchment. This is by way of determining trend of hydroclimatic parameters and the trend of expansion of sectors of economy. Three key sectors were put in consideration these are hydropower generation, crop farming (mainly paddy and sugar cane) and the environment (minimum flow value to sustain e-flow). The land use analysis was used to understand expansion of farms whereas the soil and water assessment tool (SWAT) was used to assess the interaction of hydroclimatic and land use parameters.

(i) Description of SWAT Model

Soil and Water Assessment Tool (SWAT) is a continuous time and spatially distributed basin level framework designed to simulate the quality and quantity of surface and groundwater and predict the ecosystem impact of LULC, land management practices, and climate change on daily time step, monthly or even annually (Arnold & Fohrer, 2005; Gassman *et al.*, 2007). It uses hydrologic response units (HRUs) that consist of specific land use, soil and slope characteristics (Sisay *et al.*, 2017). The HRUs are used to describe spatial heterogeneity in terms of land cover, soil type and slope class within a watershed. The relevant hydrologic parameters e.g., evapotranspiration, surface runoff, groundwater flow and sediment yield for each HRU unit are estimated by the model. The model is very useful because it has weather engine to generate the precipitation within an un-gauged watershed based on stochastic and probabilistic methods (Chilagane *et al.*, 2021).

Scholars such as Shope *et al.* (2014) have attempted to assess the capability of SWAT model to capture event-based and long-term rainfall–runoff processes in complex terrain. Results showed robustness of the model even though it is influenced by scale-dependent sensitivity of hydrologic partitioning and substantial influence of engineered features (Shope *et al.*, 2014). The SWAT model has been extensively used following a thirty years period of experimentation by the Agriculture Research Service (ARS) of the United States Department of Agriculture (USDA) (Arnold & Fohrer, 2005; Gassman *et al.*, 2007). Ever since, the tool has been used in numerous river basin globally and especially the tropical Tanzania case across majority of the nine river and lake basins (Cheema *et al.*, 2014; Parajuli *et al.*, 2018; Senkondo *et al.*, 2019; Wambura *et al.*, 2018). The SWAT is an extension of GIS interface such as ArcSWAT which is an extension of ArcGIS that is based on the water balance (Equation 14).

$$SWt = SWo + \sum_{i=1}^t (R_{day} - Q_{sur} - E_a - W_{seep} - Q_{gw}) \quad 14$$

Whereby, SW_t is final soil water content (mm), SW_o is the initial soil water content in day i (mm), t is time in a day, R_{day} is precipitation amount on specific days i (mm), Q_{sur} is the runoff amount on specific days i (mm), E_a is evapotranspiration amount on day i (mm), W_{seep} is the amount of water percolated into the vadose zones on a day i (mm) and Q_{gw} is the return amount of flow on a day i (mm).

(ii) Model Calibration and Validation

Model calibration and validation to reduce the prediction uncertainty were performed by using the Sequential Uncertainty Fitting (SUFI-2) within the SWAT-CUP (Abbaspour *et al.*, 2007). Calibration and validated was conducted using monthly flow data for the period 1962 – 1965 and 1966 – 1969, respectively. The 3 years prior to 1962 were used as a warmup period to provide steady-state condition and mitigate unknown initial conditions to the model. Four objective functions namely: Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2), Probability bias (PBIAS) and Root mean square error (RSR) were employed to assess performance of the model (Chilagane *et al.*, 2021; Mazengo *et al.*, 2022; Mutayoba *et al.*, 2018). The general performance rating statistics for selected objective function as proposed by Gyamfi *et al.* (2016) and Moriasi *et al.* (2007) were used to determine the performance of the model.

The Nash-Sutcliffe efficiency (NSE) determines the relative size of the residual variance in relationship to the measured data variance (Nash & Sutcliffe, 1970). It is used in the model to indicate how well the plot of observed versus simulated data fits the 1:1 line (Moriassi *et al.*, 2007). Nash-Sutcliffe efficiency ranges from $-\infty$ to 1 where efficiency of one ($E = 1$) corresponds to a perfect match of modeled discharge to the observed data, efficiency of zero ($E = 0$) indicates that the model predictions are as accurate as the mean of the observed data, and efficiency less than zero ($E < 0$) occurs when the observed mean is a better predictor than the model. Principally, the closer the model efficiency to 1, the more accurate the model is. The NSE is calculated following Equation 15:

$$NSE = 1 - \frac{\sum_i (Q_i - Q_s)^2}{\sum_i (Q_i - \bar{Q})^2} \quad 15$$

Coefficient of determination (R^2) is a measure of the strength of the linear correlation between the predicted and measured variables. It ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Van Liew *et al.*, 2003). It is calculated as Equation 16:

$$R^2 = \left[\frac{\sum_i (Q_i - Q_s)(Q_i - \bar{Q}_i)}{(\sum_{i=1}^n (Q_i - \bar{Q}_i))^2} \right]^2 \quad 16$$

Root means square error observed standard ration (RSR) is the measure of goodness of fit between observed and simulated time series data, is the ratio of the Root Mean Square Error (RMSE) and standard deviation of measured data. According to Legates and McCabe (1999), RSR standardizes RMSE using the observations standard deviation, and it combines both an error index and the additional information recommended. It is commonly accepted that, the lower the RMSE the better the model performance. The RSR is calculated as Equation 17:

$$RSR = \frac{RMSE}{STD_{obs}} = \frac{\sqrt{\sum_{j=1}^n (Q_j - Q_s)^2}}{\sqrt{\sum_{j=1}^n (Q_j - \bar{Q}_j)^2}} \quad 17$$

Probability BIAS (PBIAS) is the indicator of how much (in percentage) the simulated variable to be larger or smaller than their observed counterparts (Gupta *et al.*, 1999). The optimum value of PBIAS is zero, where low magnitude values indicate better simulations, positive value indicated model underestimation and negative values indicated model overestimation (Gupta *et al.*, 1999). It is calculated as Equation 18:

$$\text{PBIAS} = \frac{\sum_{i=1}^n (Q_i - Q_s)}{\sum_{i=1}^n Q_i} \times 100\% \quad 18$$

Whereby, Q_i is observed variable (e.g., discharge), Q_s is simulated variable \bar{Q}_i and \bar{Q}_i is the mean of observed variable, Q_s is the mean of simulated variable, RMSE is the root mean square error, STD_{obs} is the standard deviation of the observed variable.

(iii) Model Simulation Analysis

To assess the impacts of LULC change on the hydrology of Kilombero Catchment, the fixed change scenario (Gyamfi *et al.*, 2016; Yan *et al.*, 2013) was used to assess the influence of LULC transformation on the hydrology of the catchment. Under this scenario, the calibrated and validated model was used to simulate stream flows under changed land-use/cover condition for the years 1991, 2001, 2011 and 2021, while maintaining the same weather data, meteorological data, soil data and digital elevation model. The influences of the land use land cover change on water resource and other hydrological components were quantified by comparing SWAT outputs for the different scenario. The differences between observed outputs were used to represent the effects of land use and land cover changes on water resource in the catchment. Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) in the SWAT model was used to simulate the sediment yield from the catchments (Neitsch *et al.*, 2011). The simulated sediment yield results for the time periods 1991, 2001, 2011 and 2021 were compared to generate the difference that was then deduced to reveal the impact of LULC change on sediment yields.

3.3.4 Methodological Approach for Economic Value of Water

(i) Social Economic Data Collection

This study employed a set of approaches from the participatory rural appraisal (PRA) discussed in Chambers (1994) and Riswan (2020). This entailed: A transect walk (TW), key informant interviews (KII), household survey (HHS) and focused group discussions (FGD). Except for the HHS, which were conducted as semi-structured interview and TW which entailed physical observation, photographs and documentation, the rest were open ended interviews. This study adopted semi-structured questionnaires as data collection tool for HHS and interview guide for KII and FGD. Probing for KIIs and FGDs were open-ended to allow respondents to provide as much information as they possibly could and enable us to ask follow-up questions. Field

observations and interviews with different actors were important for triangulation of information whereby the same issue was probed and discussed through with diverse respondents. Responses were captured in questionnaire forms and additional explanations; key quotes and a general understanding of the responses were transcribed.

A range of qualitative and quantitative information pertaining to access to land, water, paddy farming practices, farming economics, access to storage and markets infrastructures were collected. In addition to that, a focused review of relevant literature was carried out to augment on the collected data and information. This included issues around land ownership and tenure in Tanzania (Maganga *et al.*, 2016), dynamics around utilization and access to wetland resources (Kangalawe & Liwenga, 2005), comparative impact of harvests due to irrigation in rainfed and irrigated lower land paddy farming in Tanzania (Wilson & Lewis, 2015), and the social economic profile based on the Ifakara district social economic profiles (Ifakara District Council, 2020). These, together with the collected data, helped to inform our conclusions especially on the analysis of profitability and value that irrigation brings in the wetland areas, which is characteristic of our study area.

(ii) Social-Economic Data Sampling

The survey was carried out in five villages that were selected purposefully with the help of the Agricultural Officer at Ifakara District Council. This was to ensure that selected villages (Appendix 7) had communities who practiced all the four small-holder paddy farming systems and sugarcane farming, hence capturing the agronomic information needed. The households surveyed were also pre-determined to have an equal mix of farming systems within villages. This was done in close consultation with village and farmers' group leaders who had a better understanding of the studied population. Respondents in the respective farming system were then randomly selected to limit biasness. In addition to that, a total of eighteen respondents were interviewed during Key Informant Interviews (KII) that documented responses from leaders and/or technical staff from seven key institutions with influence on agriculture in the study area (Appendix 8). For each of the crop, a total of 250 households were interviewed in the sampled villages (Appendix 7) following Charan and Biswas (2013) sample size recommendation Equation 19. Furthermore, in each village, a focused group discussion (FGD) was also carried out for paddy farming. These groups are constituted for farmers in irrigated conventional transplanting and flooding system (CTFS), irrigated system of rice intensification (SRI), rainfed CTFS and rainfed SRI.

The CTFS entails use of basic hand hoe, family labor, no or very limited use of fertilizer or pesticides and irrigation is not through improved canals that attracts water user fee (Upboff, 2008). On the other hand, SRI is described as an agro-ecological methodology aimed at increasing the yield of rice produced in farming. It is a low-water, labor-intensive method that uses younger seedlings singly spaced and typically hand weeded with special tools (Upboff, 2008). It promotes root systems and increase the abundance and diversity of soil organisms (Kahimba *et al.*, 2013). Table 3 provides further comparison between SRI and CTFS.

Table 3: A comparison between irrigated paddy farming under SRI and CTFS

No.	SRI farming practice	No.	CTFS farming practice
1	Transplant young seedlings, 8 – 12 days old, and certainly less than 15 days old to preserve subsequent growth potential Transplant seedlings singly, one per hill, and in a square pattern 25x25 cm, or wider if or when the soil is more fertile	1	Transplant older seedlings, 20-30 days old, or even 40 days old
2	- Transplant quickly (15 – 30 minutes after removal from nursery), - Shallow (1-2 cm deep) and vertical planting	2	Transplant seedlings in clumps of plants and fairly densely, 50 – 150 plants per m ²
3	Keep paddy soil moist, but not continuously saturated, so that mostly aerobic soil conditions prevail	3	Maintain paddy soil continuously flooded, with standing water throughout the growth cycle
4	Control weeds with frequent weeding by a mechanical hand weeder (rotating hoe or cono weeder) that also aerates the soil	4	Use water to control weeds, supplemented by hand weeding or use herbicides
5	Apply as much organic matter to the soil as possible; can use chemical fertilizer, but best results from compost, mulch etc.,	5	Use chemical fertilizers to enhance soil nutrients

Sato *et al.* (2007) and Uphoff *et al.* (2011)

$$\text{Sample size} = \frac{Z_{1-\alpha/2}^2 P(1 - P)}{d^2} \quad 19$$

Whereby,

$Z_{1-\alpha/2}$ = standard normal variate (at 5% type 1 error ($P < 0.05$) it is 1.96 and at 1% type 1 error ($P < 0.01$) it is 2.58). As in majority of studies P values are considered significant below 0.05 hence 1.96 is used in formular.

P = Expected proportion in population based on previous studies or pilot studies (i.e., proportion of farming households is 80% in rural areas (NBS, 2013).

d = Absolute error or precision – decided by researcher.

Therefore:

Sample size = [(1.962) x 0.80 x (1-0.80)]/0.052 = 245.86

The current study interviewed 250 Households.

(iii) Calculation of Physical Water Productivity

Physical water productivity (PWP) which is defined as the physical quantity of yield (Y) derived from the use of a given quantity of water (Molden *et al.*, 2003) was calculated using Equation 20 and specifically for agricultural water productivity Equation 21 and 22. The former was used to assess actual PWP in irrigated systems while the latter was evaluated to get an ideal value that improvement of water productivity should aim to achieve. During wet season where there is no or negligible irrigation, the PWP was calculated using only effective rainfall value.

$$PWP = \frac{\text{Quantity of yield } (Y)}{\text{Applied or Abstracted Water } (m^3)} \quad 20$$

$$PWPr = \frac{Y}{ETc} \quad 21$$

$$PWPi = \frac{Y}{P + I} \quad 22$$

Whereby, Y is yield per drop of water used e.g., kWh/m³ or Kg/m³, P is precipitation in mm, I is irrigation water in mm and ETc is crop evapotranspiration in mm.

Where actual measurements were not done, the water abstraction by Rufiji Basin Water Board (RBWB) was used in the calculations. This was guided by working assessment by RBWB who indicated that variance between permitted and actual water use is less than 10% in KRC (RBWB, 2015). This is attributed to the fact that, the study area is one of areas receiving better rains in the larger Rufiji River Basin (WREM & RBWB, 2013b). In addition, the area is not yet highly developed (e.g., accessibility) to attract a lot of investments and that farming is generally concentrating around the wetland where soils are moist and hence not much departure from permits (RBWB, 2015). For farming, water use was divided into three components i.e., crop water requirement or crop evapotranspiration (ETc), Effective rainfall/precipitation (P) and Irrigation water (I). The water uses in Kihansi HEP, Sugar Plantation and KPL mechanized system were based on their real time monitoring of water use. Furthermore, for paddy farming in small-holder farmers, split between SRI and CTFS was based on questionnaire response on farmers experience where 60% water serving was adopted for SRI. This agrees well with other

researchers on comparison of water uptake between CTFS and SRI (Kahimba *et al.*, 2013; Kavishe *et al.*, 2021).

All the three water use components were then modelled through CROPWAT 8.0 developed by FAO that considered dependable rainfall method which is recommended in these wetter areas following Equation 23 and 24 (Bokke & Shoro, 2020; Nagy *et al.*, 2010).

$$P_{eff} = 0.6 * P - 10 \text{ for } P_{month} \leq 70 \text{ mm} \quad 23$$

$$P_{eff} = 0.8 * P - 24 \text{ for } P_{month} > 70 \text{ mm} \quad 24$$

(iv) Calculation of Economic Water Productivity

The Economic Value of Water (EVW) or economic productivity of water was evaluated using the Residual Imputation Approach (RIA) which means identification of the unknown incremental influence of an input after isolation of the known inputs from the value of the total output. The derivation of the ‘residual’ value of water in this approach was based on two principal postulates as discussed elsewhere (Chiang, 2005; Kadigi *et al.*, 2004; Mdemu *et al.*, 2013; Musamba *et al.*, 2011; Sigalla *et al.*, 2022; Young, 1996):

- a) Competitive Equilibrium: Which requires that the prices of all resources be equated to returns at the margin. “Profit-maximizing” producers are assumed to add productive inputs up until the point when the Value Marginal Products (VMPs) are equal to opportunity costs or “Value” of the inputs,
- b) The Total Value of Product (TVP) can be divided into shares, so that each resource is paid according to its Value Marginal Product (VMP) and the TVP is thereby completely exhausted.

For an agricultural production process, for example, in which paddy output (Y) is produced by the following factors of production: Capital (C), labor (L), and other natural resources [e.g., land (R) and irrigation water (W)]. The production function can be written as Equation 25. In this case the value of water is not lumped because all the other inputs of production are considered as opposed to other approaches such as the Change in Net Income (Hussain *et al.*, 2001). This approach assumes the average value of water as a ratio of product subtracting the net value of product that is produced while incorporating the consumed water and that without water use to the amount of water used. Here there is no consideration of other inputs of production that contribute to the net value of product in question.

$$Y = f(C, L, R, W) \quad 26$$

By the second postulate, it then follows that:

$$TVPY = (VMP_C \times Q_C) + (VMPL \times QL) + (VMPR \times QR) + (VMPW \times QW) \quad 27$$

Whereby, TVP represents Total Value of Product, Y ; VMP represents Value Marginal Product of resource i ; and Q is the quantity of resource i . The first postulate, which asserts that value P of product i is represented by $P_i = MPV_i$, permits substitution of P_i into Equation 26 and rearrangement of the same Equation as follows:

$$TVPY - [(P_C \times Q_C) + (PL \times QL) + (PR \times QR)] = PW \times QW \quad 27$$

On the assumption that all variables in Equation 27 are known except PW, that expression can be solved for that unknown to impute the value (shadow price) of the residual claimant, (water) PW , as in Equation 28:

$$PW = \{TVPY - [(P_C \times Q_C) + (PL \times QL) + (PR \times QR)]\} / QW \quad 28$$

3.3.5 Methodological Approach to Assess Hydro-Economic Tradeoffs

(i) Calculation of Marginal Productivity of Water

In the current research work, a comparison of the amount of water used vs the generated income was important to understand the contribution of water in the sectors of economy. Furthermore, to establish sound tradeoff(s) on where additional drop of water had most economic return, this study employed Marginal Productivity of Water (MPW). Studying MPW is important for study the additional outputs gained by using an additional unit of water while keeping other inputs unchanged, as shown in previous research (Hailu, 2017; Mukherjee *et al.*, 2012). The current study expands on the existing paradigm by analyzing the marginal productivity of water in relation to paddy farming, sugarcane cultivation, and hydroelectric production (HEP).

The research attempts to offer a detailed understanding on how alterations in water usage affect production outcomes in these key sectors of economy in the Kilombero River Catchment, Tanzania at large and sub-Saharan Africa in general. The analysis entails a thorough investigation of the correlation between the fluctuations in production, quantified in US\$ and their associated variations in water consumption as documented from the riparian district's

social economic profiles and water use permits from Rufiji Basin Water Board. As such, the MPW is presented as the ratio of the change in profit to that of volume of water used between two consecutive years in a decade between 2011 and 2021 (Equation 29).

$$MPW = \frac{\Delta Change\ in\ profit}{\Delta Change\ in\ Water\ use} \quad 29$$

(ii) Gross Profit Margins and Return on Investment

Since paddy farming fetched the least in PVW and MPW while it is the major livelihood, it was necessary for this study to further assess which of the paddy farming systems was more potential in both return to communities as well as water serving. In this regard, profitability assessment was necessary. The calculation of the same was based on determining gross profit margin (GPM) and return on investment (ROI) of all the farming systems. These were calculated as a ratio of profit to accrued income and to farming outlay (Equation 30 and 31) as discussed elsewhere (Eriotis *et al.*, 2011; Nariswari & Nugraha, 2020; Özçelik, 2015). Data were obtained from questionnaire analysis where minimum, maximum and average value were established together with other statistical descriptions. Some questionnaires (less than 5%) had missing responses in some of questions and in this case, they were omitted in the data processing.

Responses were also coded to capture similar meaning in same category of interpretation as discussed by Dolmaz (2019). Analysis of data were performed in Microsoft Excel interface and results were then presented in the form of tables, pie charts and graphs that enabled comparison and contrasting of researched aspects.

$$Gross\ Profit\ Margin = \frac{Revenue - Costs}{Revenue} \times 100\% \quad 30$$

$$Return\ on\ Investment = \frac{Revenue - Costs}{Costs} \times 100\% \quad 31$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Spatial Variability Hydroclimatic Parameters

Owing to availability of data, spatial trends were only carried out for key climate variable viz. precipitation, temperature and evapotranspiration. This indicated that there were mainly three climatic zones i.e., Mahenge escarpment (SW parts of the catchment), the Kilombero valley (constituting the middle lower laying part) and the Udzungwa escarpment (forming the westerly boundary of the catchment). According to this research, Mahenge escarpment received high rainfall (1500 – 2100 mm), and the condition declined in the westerly direction to Udzungwa receiving about 1800 – 2000 mm of rainfall (Näschen *et al.*, 2018; Sigalla *et al.*, 2023).

The same pattern was indicated by evapotranspiration and temperature variables where values declined with a westerly direction. Most specifically though, it was the hottest and most evaporation in the NE parts of the valley and coolest and least evapotranspiration at the middle parts of the western boundary of the catchment (the Udzungwa escarpment). Figure 3 illustrates the state of climate zones in Kilombero river catchment. The westerly changing climate pattern is influenced by altitude, distance from the Indian Ocean and proximity to dense forests e.g., Nyerere and Udzungwa forests. This spatial climate variability can be explained by the fact that Mahenge and Udzungwa Mountains intercepts moisture-laden winds from the Indian Ocean and hence receive more rainfall than the surrounding lowlands (Koutsouris, 2017; Koutsouris *et al.*, 2016). Orographically, Mahenge escarpment receive these winds earlier and benefit more than Udzungwa mountains although they are the highest.

Furthermore, proximity to the expansive Miombo Forest that forms part of Nyerere National Park (formerly Selous Game Reserve) and Udzungwa forest could explain the more rainfalls received in Mahenge and Udzungwa escarpments, respectively. These Indian Ocean winds and forest also presented similar influence on other climate parameters discussed here. Because the lower laying valley is encapsulated by the Udzungwa, Mbarika and Mahenge escarpments and lack populated forests, it tends to be warmer and received the lowest rainfall amounts.

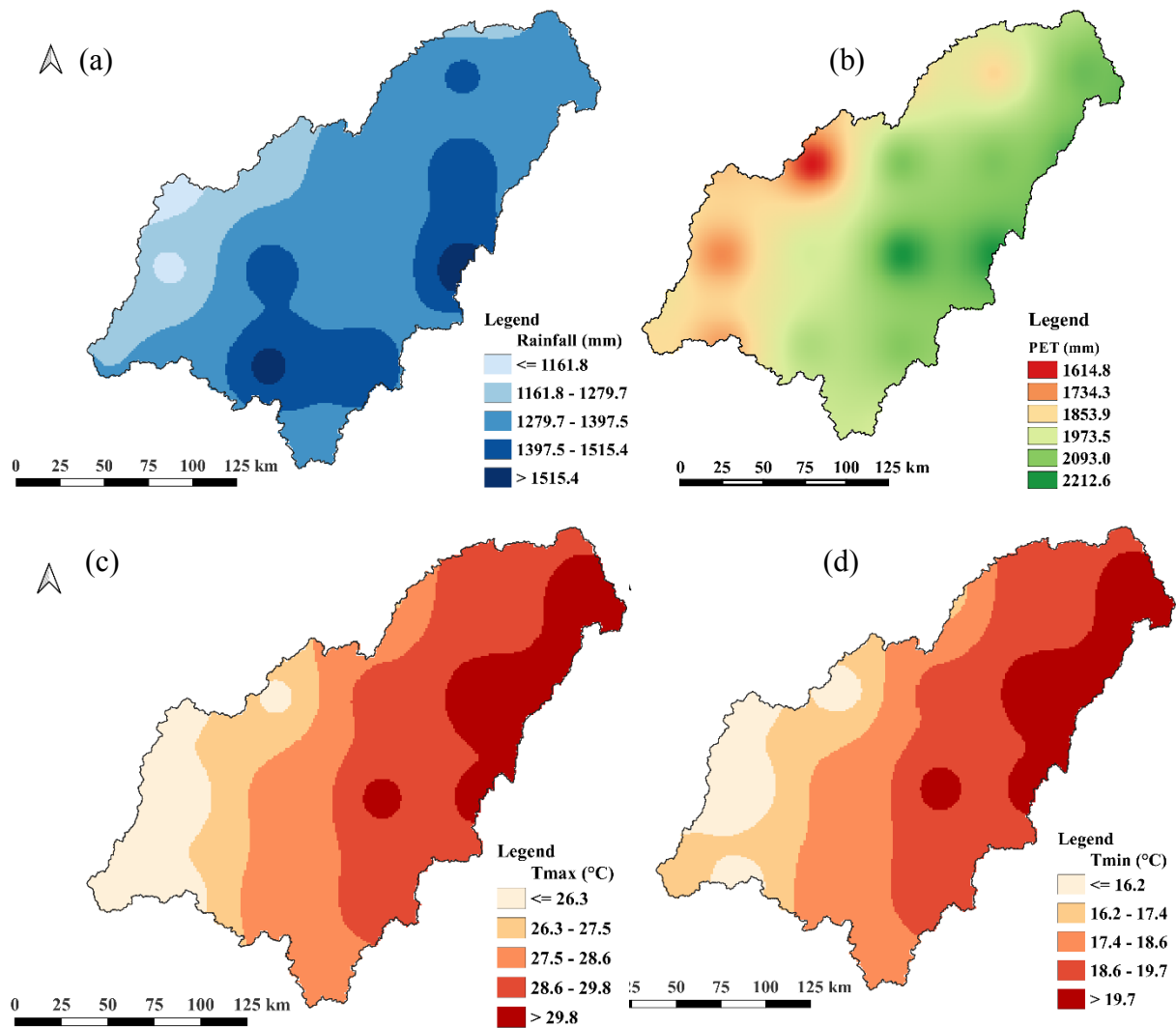


Figure 3: Spatial distribution of climate variables; (a) Rainfall, (b) Potential Evapotranspiration, (c) Tmax, and (d) Tmin

4.2 Temporal Variability of Hydroclimatic Parameters

From the climate zones determined in spatial analysis above, the three zones made basis for trend analysis. These zones were also identified by other scholars who carried out similar climate study in the area such as Koutsouris *et al.* (2016) and Näschen *et al.* (2018). The trend analysis for all three zones and one for averaged variables for entire Kilombero catchment were performed. In addition, hydrology data were equally assessed using the most strategic/downstream station in the catchment i.e., Kilombero at Swero (hydrologic Ref. No.: 1KB17) which records the water volume discharged out of Kilombero catchment after all tributaries and water uses upstream.

Furthermore, the long-term observed and satellite data between 1981 and 2019 were used to get descriptive statistics for each individual month to assess seasonality of variables in the

catchment, the general long-term statistical trend and the magnitude of increasing or decreasing trend. Results for all these variables are presented in subsequent sections.

4.2.1 Historical Precipitation Pattern

(i) Seasonality of Precipitation

Evaluation of long-term precipitation data showed that, in all climate zones and consideration of the entire catchment, a unimodal rainfall pattern was experienced. The onset is generally around November, and it faded away in May. Peak rainfall was experienced in March for the mountainous areas of Udzungwa and Mahenge whereas it was experienced in April around Kilombero valley and under entire catchment consideration (Fig. 4; Temporal variation shows a unimodal rainfall pattern commencing around Nov and ends by May). In addition, all the four considerations (i.e., three climate zones and a whole catchment average) showed evenly distributed monthly values (median value closer to mean). Furthermore, the data showed that, the interquartile range (IQR) for less rainfall months is small, indicating 50% of the data are tightly packed and so the average value is more useful to characterize rainfall in a particular month.

The unimodal nature of rainfall pattern in the catchment is associated with the position of inter tropical convergence zone (ITCZ) which does not linger over the southern and western to central parts of Tanzania (Näschen *et al.*, 2018; Senkondo *et al.*, 2017). This causes the precipitation centers in the months of September-October-November (SON) to be very low to insignificant with substantial rains observed until December whereas the March -April-May (MAM) precipitation center being the most dominant (Borhara *et al.*, 2020; Näschen *et al.*, 2018). Furthermore, in all the four considerations, the results presented a consistent delay of rainfall for about a month. Whereas hydrologic year for Tanzania starts in October and ends in September, rainfall in the catchment mostly started in November. This could partly be explained by the distance from Indian ocean (with moist air) travelling and be blocked by Mahenge and Udzungwa escarpments which manifest the orographic rainfall processes that was noted to be characteristic of the study area.

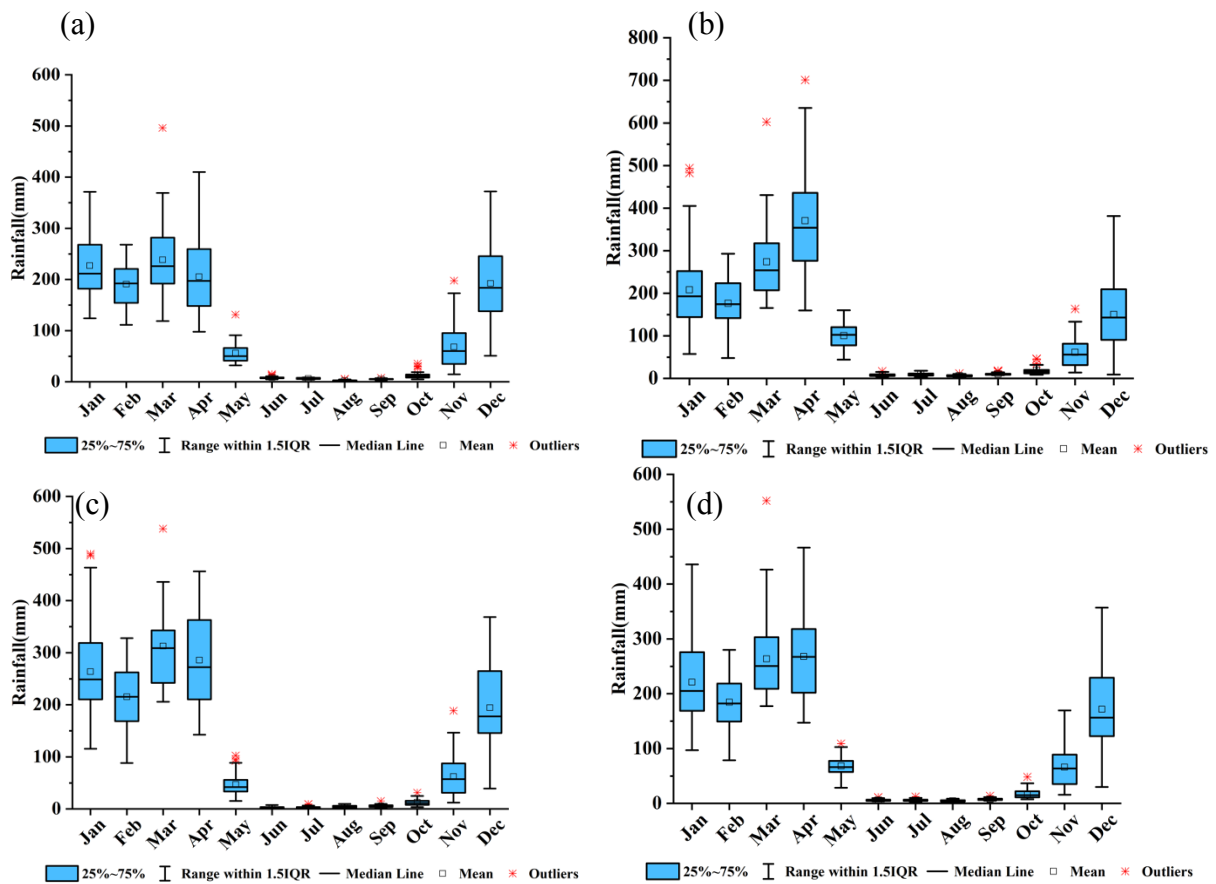


Figure 4: Seasonality of rainfall in (a) Udzungwa zone, (b) Kilombero Valley, (c) Mahenge zone and (d) Average for whole Kilombero Catchment

(ii) Long-Term Statistical Trend – Precipitation

Results for statistical test of rainfall variable for the three zones under consideration and the entire catchment are summarized in Table 4 and illustrated in Fig. 5 (Data showed sharper increase from early 2000s attributable to regional recovery from the 1970s and 1980s severe drought periods). According to the statistical test results, there was an increasing trend of rainfall under all four considerations. However, only in Mahenge escarpment was the trend not statistically significant.

Closer observation of graphs as presented in Fig. 6 show a general increase in precipitation from the early 2000s. This increase may be attributable with the observation made by Chaney *et al.* (2014) that, the East African region was recovering from the 1970s and 1980s periods of severe droughts hitting Ethiopia, Kenya and Tanzania. However, while agreeing with this reasoning, Gebrechorkos *et al.* (2019), recommended some courteousness in the reasoning that future is brighter based on what they argued that the increasing trend in precipitation is weak. In the current study, the magnitude of the increasing trend was 2.08 mm/year for the whole catchment average. The rest of the climatic zones were as presented in the Sen’s slope values in Fig. 7.

However, the indicated general increase in rainfall for all the considered climatic zones under this study doesn't entirely agree with other scholars. Perhaps due to finer scale of study, this contradicted with results in other coarser scale studies where a general decrease in precipitation in southern highlands of Tanzania was observed (Borhara *et al.*, 2020; Luhunga *et al.*, 2018). This increase in rainfalls is expected to have adverse effects in nutrient leaching, erosion of topsoil, water logging, new pests, diseases outbreak that could affect agricultural production while infrastructure damages may lead to food supply issues (IPCC, 2007; URT, 2003).

Table 4: Summary of statistical test results for rainfall variable at confidence level of 95% ($\alpha=0.05$)

N	Climate Zone	Z	Sen's slope	S	Var (s)	Kendal tau	P- value
1	Udzungwa escarpment	1.55	3.73	134.00	7366.67	0.17	0.12
2	Kilombero Valley	1.01	4.34	88.00	7366.67	0.11	0.31
3	Mahenge escarpment	0.50	1.65	44.00	7366.67	0.06	0.62
4	Kilombero Catchment	0.92	2.08	80.00	7366.67	0.10	0.36

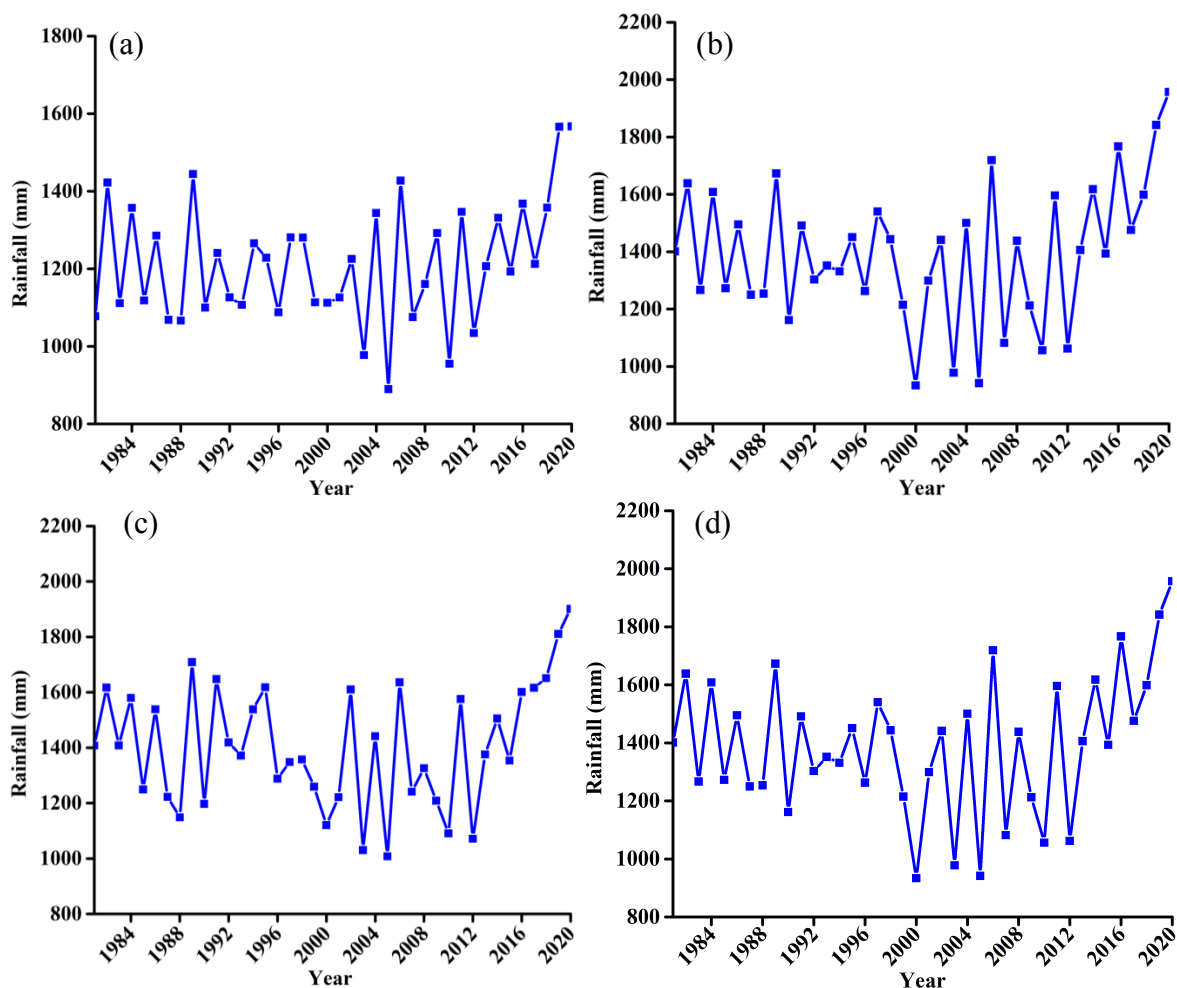


Figure 5: Long-term precipitation timeseries trend for: (a) Udzungwa zone, (b) Kilombero Valley, (c) Mahenge Zone and (d) Average for whole Kilombero Catchment

4.2.2 Historical Temperature Pattern

(i) Seasonality of Temperature

The seasonality of T_{max} and T_{min} for all the four considerations were assessed using the maximum, mean, median, the lowest and the highest monthly value ever experienced. This showed that, on both cases months of June to August (JJA) were the coolest (Fig. 6 and 7). Whereas for T_{max} , the months of October to December (OND) recorded the highest values or the warmest (Fig. 6) in the case of the T_{min} the high values continued to around March (Fig. 7). The spatial analysis showed that Udzungwa experienced the coldest weather, followed by Mahenge and then the middle valley portion especially the NE parts which were the warmest in the study area. In addition, the display of results helps to not only consider the average value to characterize a particular month and hence season but also actually helps to understand the range especially that of the 50% of data i.e., between 25 and 75 percentiles (i.e., Q1 and Q3) hence giving the IQR as a measure of spread of these 50% of data.

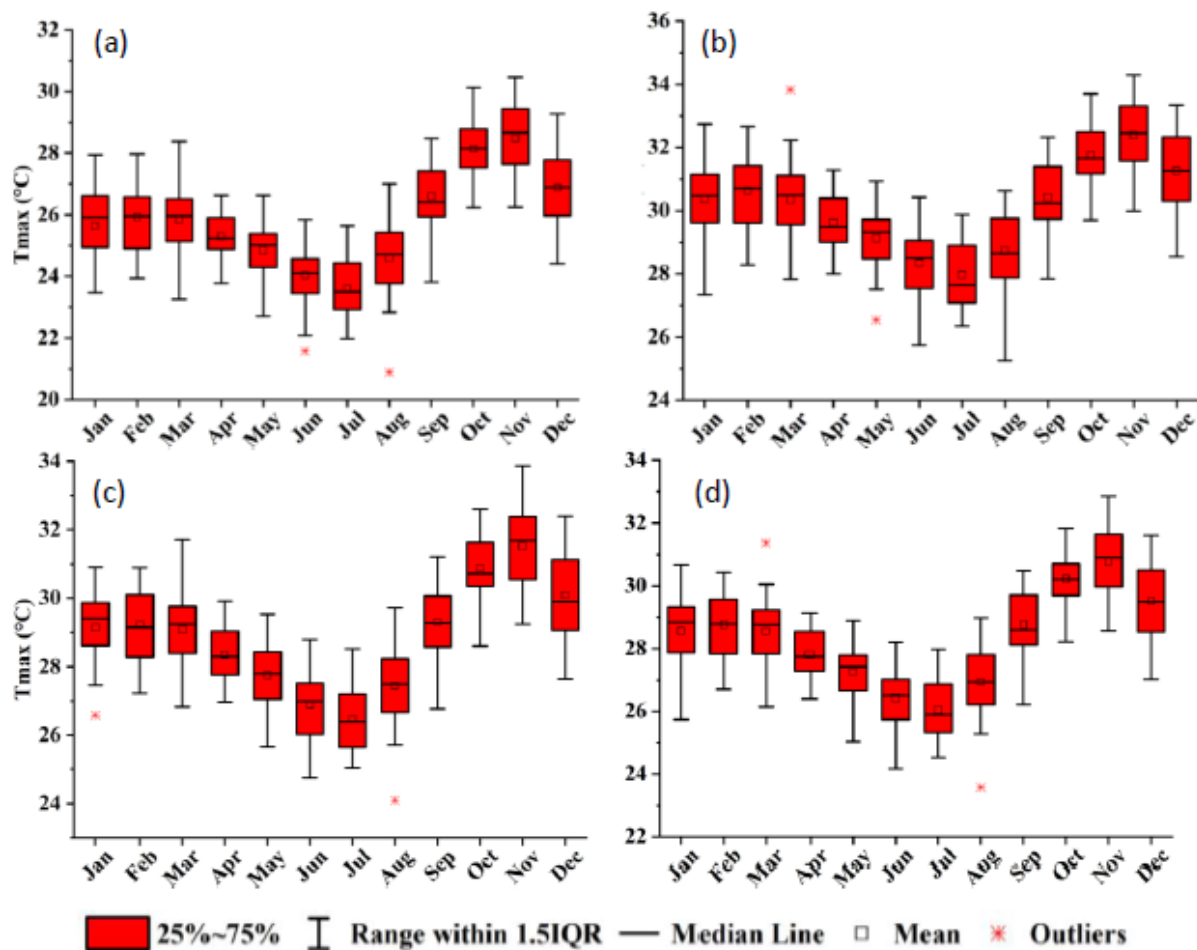


Figure 6: Seasonality of T_{max} for: (a) Udzungwa zone, (b) Kilombero Valley, (c) Mahenge Zone and (d) Average for whole Kilombero Catchment

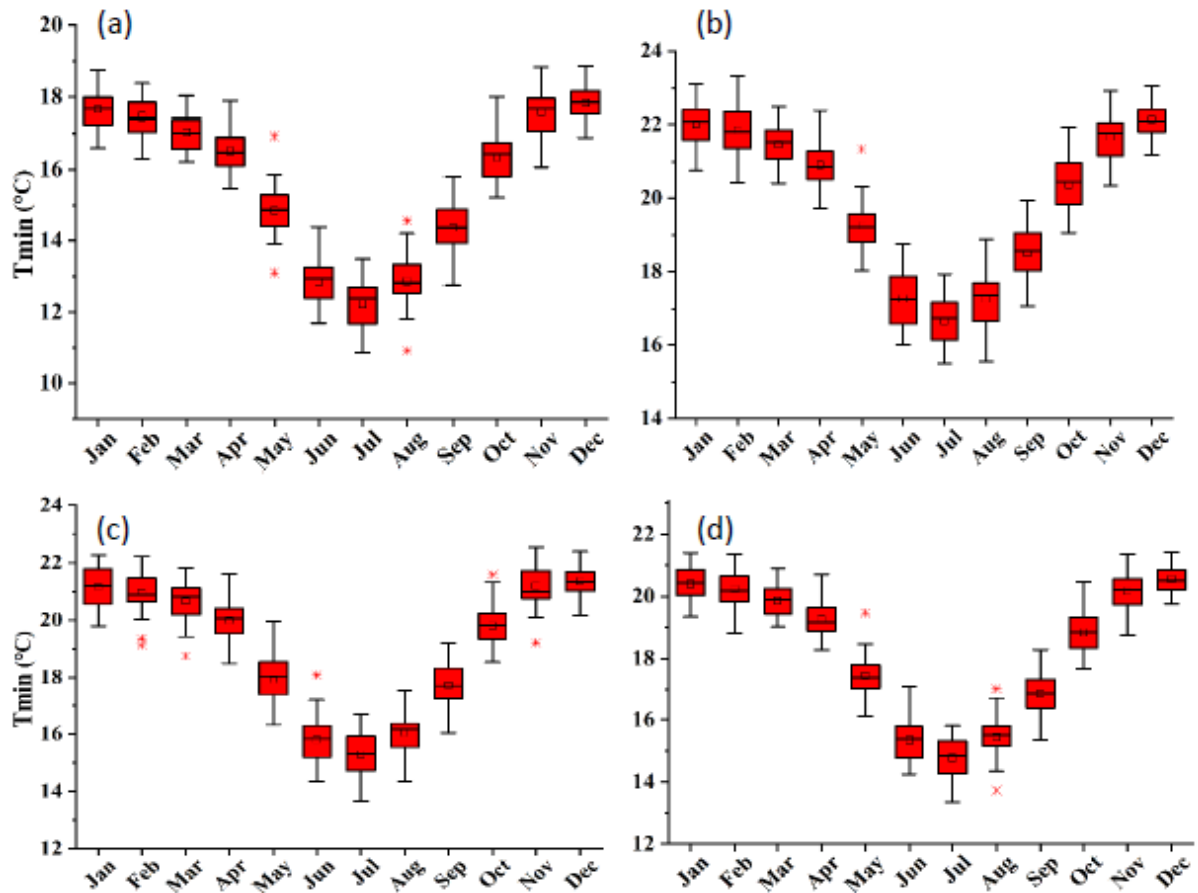


Figure 7: Seasonality of T_{min} for: (a) Udzungwa zone, (b) Kilombero Valley, (c) Mahenge Zone and (d) Average for whole Kilombero Catchment

(ii) Long-Term Statistical Trend – Temperature

Table 5 and 6; and Fig. 8 and Fig. 9, respectively give a summary and illustration for the statistical results of T_{max} and T_{min} for the four zones considered in this analysis. These showed that, there was a significant increasing trend of T_{max} and T_{min} for all the four zones. Considering T_{max} variable alone, the magnitude of increasing trend was $0.05^{\circ}\text{C}/\text{y}$ for all the four considered climatic zones. On the other hand, consideration of T_{min} variable showed a magnitude of increasing temperature for $0.02^{\circ}\text{C}/\text{y}$ for Mahenge and entire catchment as compared to an increase of $0.03^{\circ}\text{C}/\text{y}$ for Udzungwa and Kilombero valley zones.

In addition, whereas T_{max} sharp increase occurred in the early 2000s, that of T_{min} started around mid-90s. This was consistent with observation by Gebrechorkos *et al.* (2019) who indicated the same for the east African region considering Ethiopia, Kenya and Tanzania. This was attributed to warming of sea surface temperature particularly in the southwest Indian Ocean together with the inter-annual climate variability i.e., El Niño/Southern Oscillation (ENSO) that is suggested to play a key role in East African weather (Case, 2006; Hussein, 2011; Plisnier *et al.*, 2000).

The probable impacts of increase in temperature according to Hatfield *et al.* (2014), include effects on the immunity of livestock to diseases and finally reduces the fertility and milk production.

Changes in temperature and precipitation have direct (e.g., thermal stress, eye diseases, skin cancer, and waterborne diseases, ultimately affecting mortality and morbidity) and indirect (e.g., malnutrition, diarrhea and malaria and dengue fever) impacts on human health (Song *et al.*, 2017; Wichmann, 2017). Considering the above example and other related impacts of changing in extremes, there is a need to improve the current forecasting system and awareness at different levels, particularly regional-local and across sectors to manage the risks. In addition, countries should make their meteorological data easily accessible for research to develop climate projections and sustainable adaptation and mitigations strategies.

Table 5: Summary of statistical test results for Tmax variable at confidence level of 95% ($\alpha=0.05$)

N	Climate Zone	Z	Sen's slope	s	Var (s)	Kendal tau	P- value
1	Udzungwa escarpment	4.37	0.05	0.00	0.00	0.00	0.00
2	Kilombero Valley	4.39	0.05	378.00	7366.67	0.48	0.00
3	Mahenge escarpment	4.81	0.05	414.00	7366.67	0.53	0.00
4	Kilombero Catchment	4.53	0.05	390.00	7366.67	0.50	0.00

Table 6: Summary of statistical test results for Tmin variable at confidence level of 95% ($\alpha=0.05$)

N	Climate Zone	Z	Sen's slope	s	Var (s)	Kendal tau	P- value
1	Udzungwa escarpment	4.39	0.03	378.00	7366.67	0.48	0.00001
2	Kilombero Valley	4.58	0.03	394.00	7366.67	0.51	0.00001
3	Mahenge escarpment	2.23	0.02	192.00	7366.67	0.25	0.02606
4	Kilombero Catchment	3.72	0.02	320.00	7366.67	0.41	0.00020

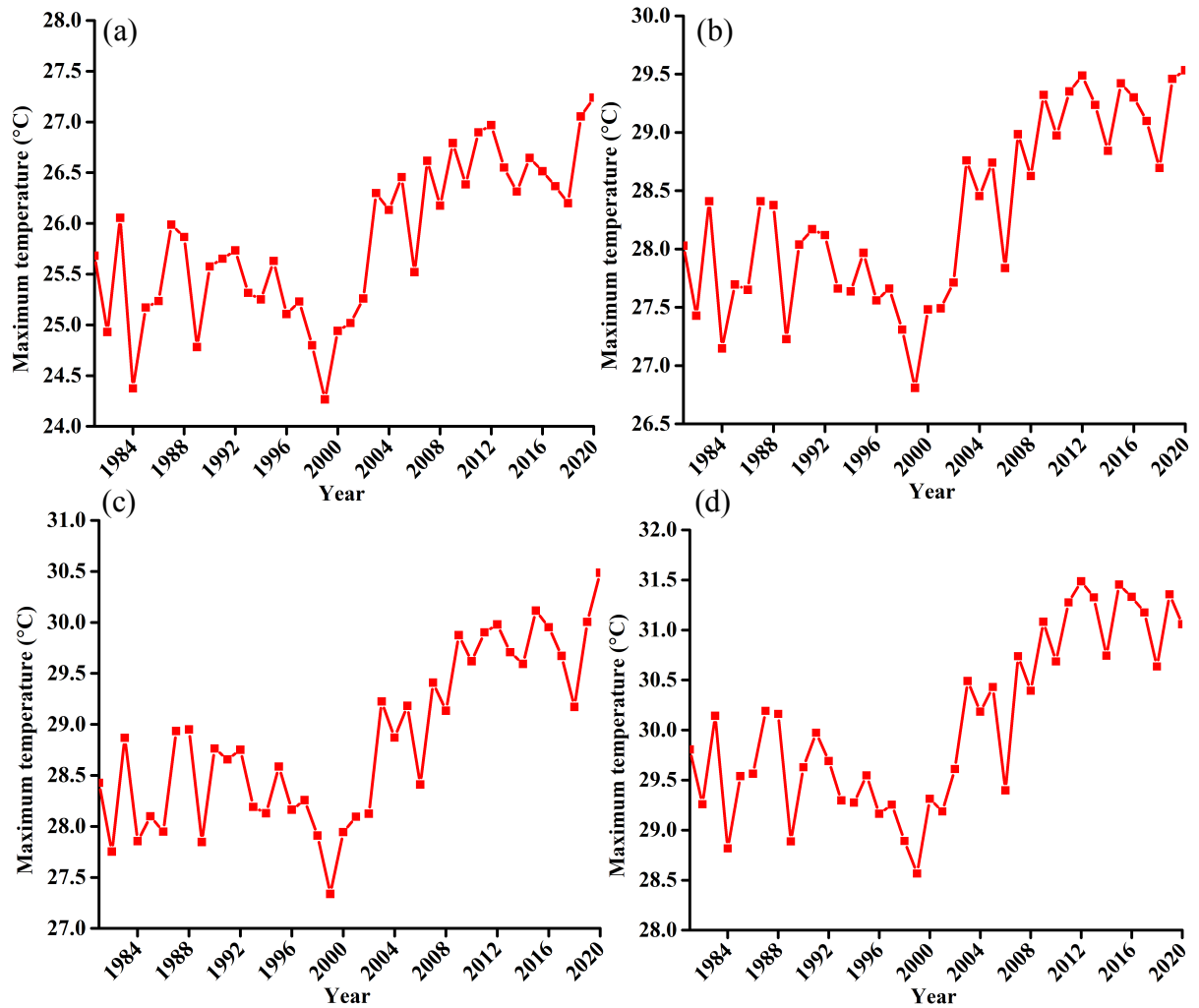


Figure 8: Long-term Tmax timeseries trend for: Udzungwa zone (a), Kilombero Valley (b), Mahenge Zone (c), and average for whole Kilombero Catchment (d) illustrating an increasing trend throughout the climatic zones

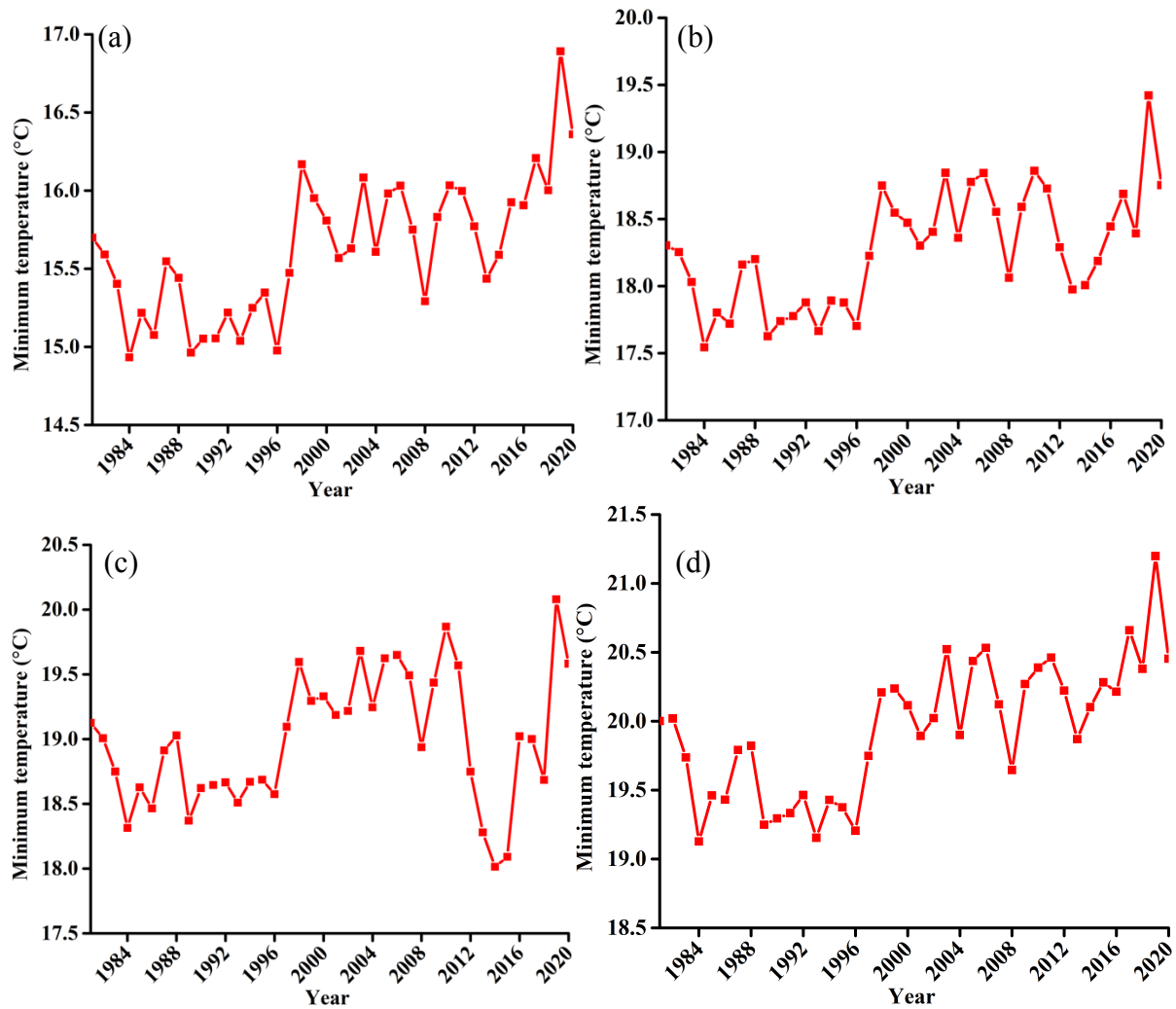


Figure 9: Long-term T_{min} timeseries trend for: Udzungwa zone (a), Kilombero Valley (b), Mahenge Zone (c), and Average for whole Kilombero Catchment (d)

4.2.3 Historical Potential Evapotranspiration Pattern

(i) Seasonality of Potential Evapotranspiration

As was the case for other variables, descriptive statistics were used to indicate the seasonality pattern of potential evapotranspiration (PET). Results showed similar seasonal rise and fall of PET values but in this case the latter comes earlier by a month (i.e., June) in all cases (Fig. 10) compared to temperature variable. This might mean that evaporation intensified when there was enough hotness/heat which happened in latter months. These catchment areas are known to be relatively humid and with low wind and radiation which is attributed to higher altitude and topography associated with the famous east African rift system-mountain ranges (Alfayo & Uiso, 2002). In addition, KRC has thicker forests as compared, for instance, to the Great Ruaha River catchment further west. The forest cover is thicker and expansive from the eastern half of the catchment forming the Nyerere National Park (formally Selous game reserve) which is about 50 000 km² (Jaeger *et al.*, 2014), almost a third of entire England with 132 932 km².

These forests might be instrumental in blocking and/or reducing wind activity from the Indian Ocean inland towards this catchment hence exacerbate humidity.

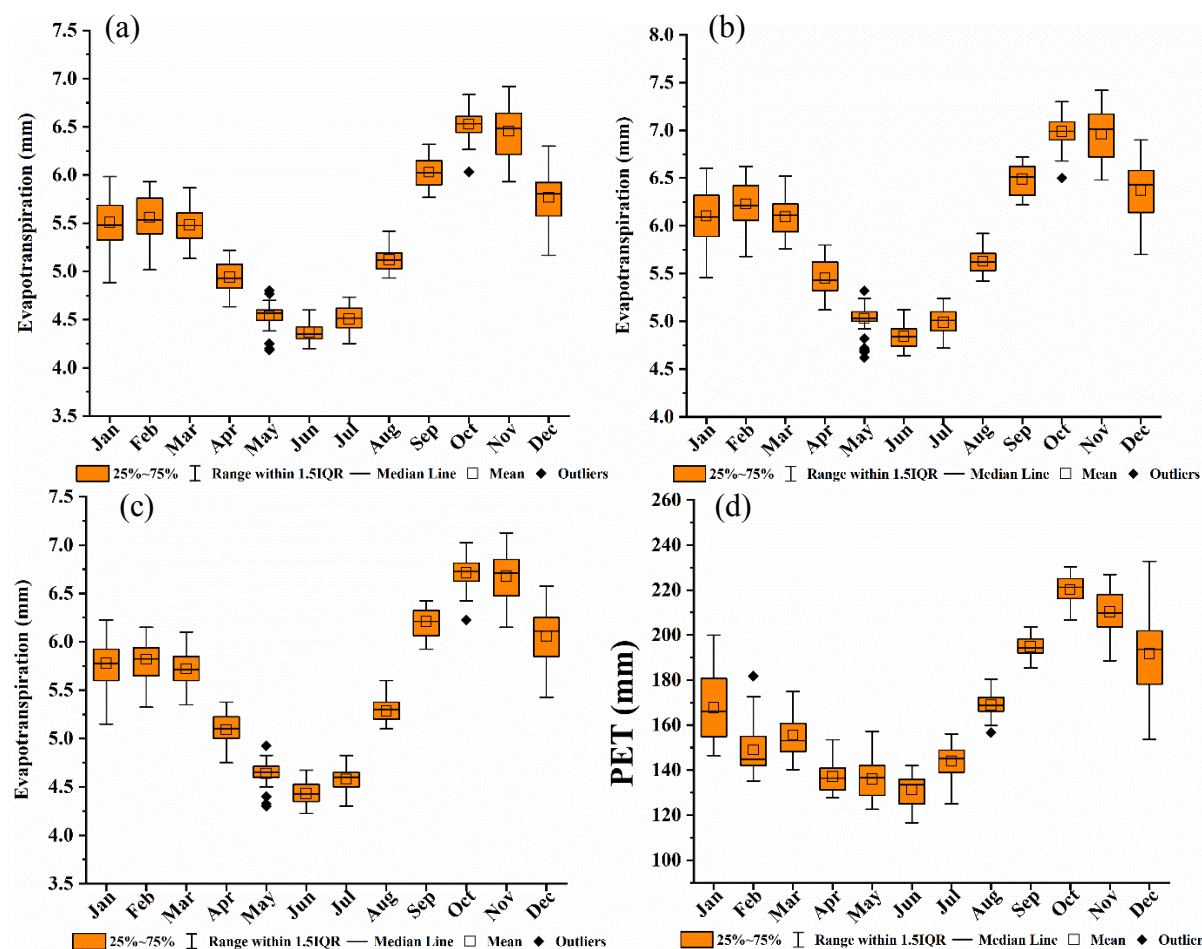


Figure 10: Seasonality of potential evapotranspiration for: Udzungwa zone (a), Kilombero Valley (b), Mahenge Zone (c), and Average for whole Kilombero Catchment (d)

(ii) Long-Term Statistical Trend - PET

The test statistical results for evaporation variable are summarized in Table 7 and illustrated in Fig. 11. These results consistently show a statistically decreasing trend for all four considerations and an average drop of 2.77 mm/yr for the catchment average. Other climatic zones are as shown in Fig. 6. A close observation of results in Fig. 11 presented the opposite trend from the other variables with the onset of evaporation declination from early 2000s. Since these areas receives high rainfall but situated in high attitude areas with dense forest, it was interpreted that winds necessary to maintain low humidity was reduced significantly by blockage from trees and mountains as indicated in Jaeger *et al.* (2014) and Alfayo and Uiso (2002) who, respectively, looked at global manifestation of climate variables especially evapotranspiration and the role of Selous game reserve forests to local climates. In this regard,

since temperatures are ever increasing, it is rainfall that affects the presence of moisture content in the air and hence low possibility of evaporation where winds are weak.

Table 7: Summary of statistical test results for evaporation variable at confidence level of 95% ($\alpha = 0.05$)

N	Climate Zone	Z	Sen's slope	s	Var (s)	Kendal tau	P- value
1	Udzungwa escarpment	-0.99	-0.76	-83.00	6833.67	-0.11	0.32
2	Kilombero Valley	-2.73	-3.03	-227.00	6833.67	-0.31	0.01
3	Mahenge escarpment	-3.24	-2.33	-269.00	6833.67	-0.36	0.00
4	Kilombero Catchment	-2.77	-1.86	-181.00	6833.67	-0.24	0.03

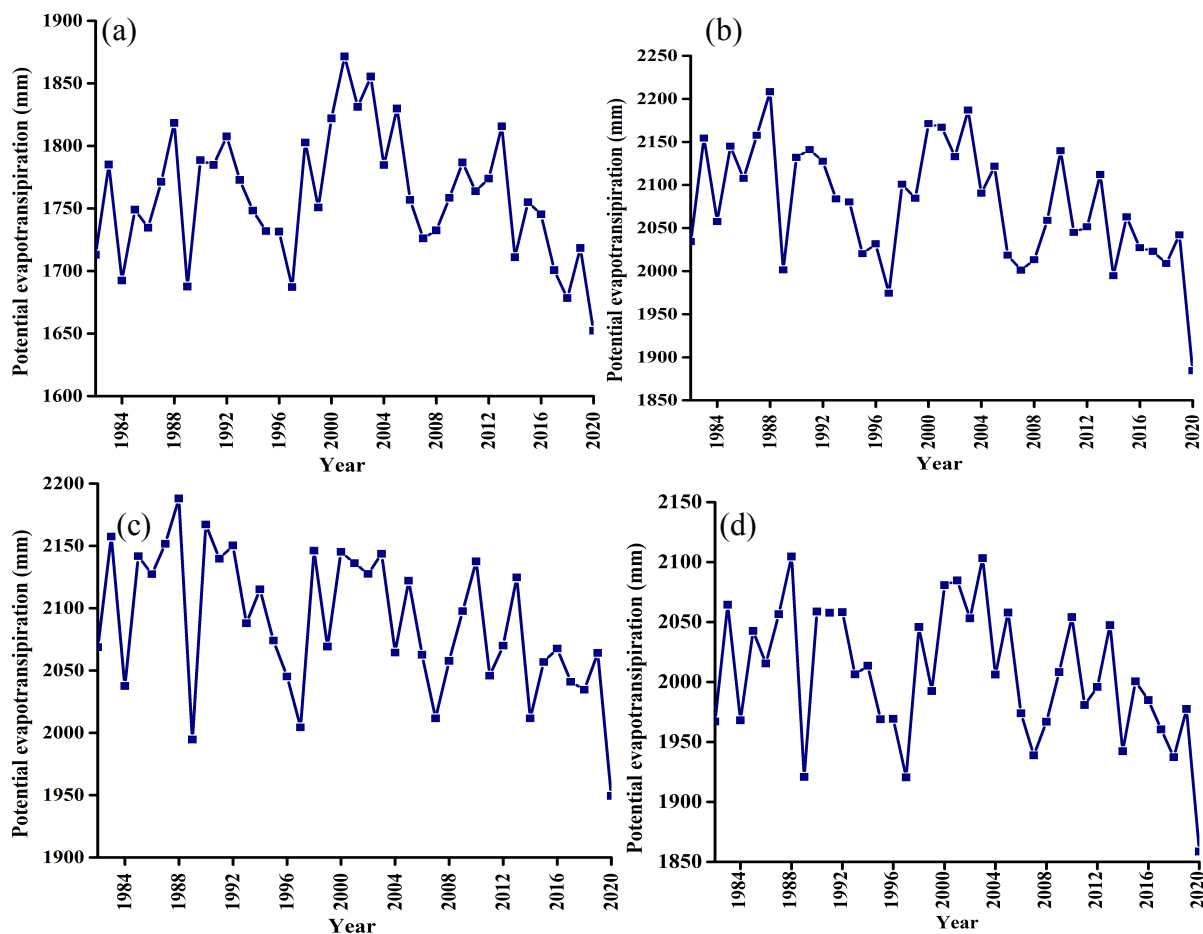


Figure 11: Long-term evaporation timeseries trend for: Udzungwa zone (a), Kilombero Valley (b), Mahenge Zone (c), and Average for whole Kilombero Catchment (d)

4.2.4 Historical River Discharge Pattern

The long-term trend analysis and seasonality for river discharge were also carried out using data from the most downstream gauge station i.e., Kilombero at Swero (1KB17). According to this analysis (Fig. 12), the river discharge increased at a rate of 498.6 m³/s. Other statistical results for this test were as follows: Z-statistics were 4.477 and p-value was 0.0000076. These statistics showed a statistically increasing trend. Since evaporation is on the fall and

precipitation is on the increase, one would logically agree with the increasing river discharge. However, the rapid expansion of farming activities as presented in subsequent sections would suggest a reduced flow downstream since farming is the largest consumptive user of water. The recorded increment in river discharge could then be attributable to sediment piling at gauge station site, which could have been giving elevated stuff-gauge value. It should be noted that, the station is in the game-protected area with stable banks (rocky and vegetated), which suggests that the origin of sediment must be upstream (Plate 1 and 2).

In addition, seasonality analysis for this station showed a peak flow in April and the lowest flow in November. Comparison of rainfall seasonality with river discharge showed a quick response between the two variables. This suggested that runoff is higher than groundwater recharge component as determined in subsequent sections. This is especially true in an area where most rain falls further upstream in Udzungwa and Mahenge escarpments. The range in seasonal river discharge indicated a highly variable flow pattern.

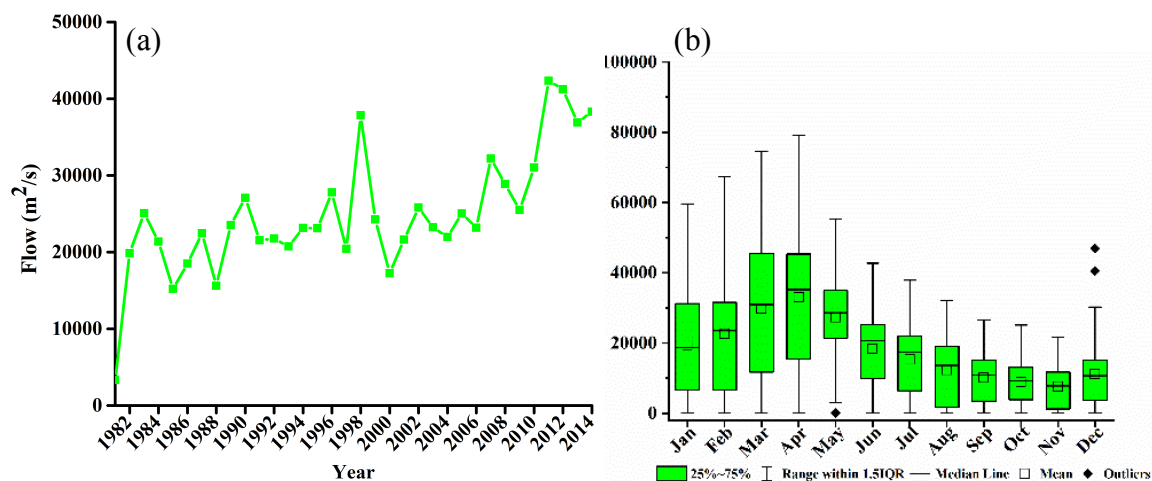


Figure 12: Temporal variability of river discharge for: Kilombero at Swero (1KB17) gauge station Long-term trend (a) and Seasonality (b)

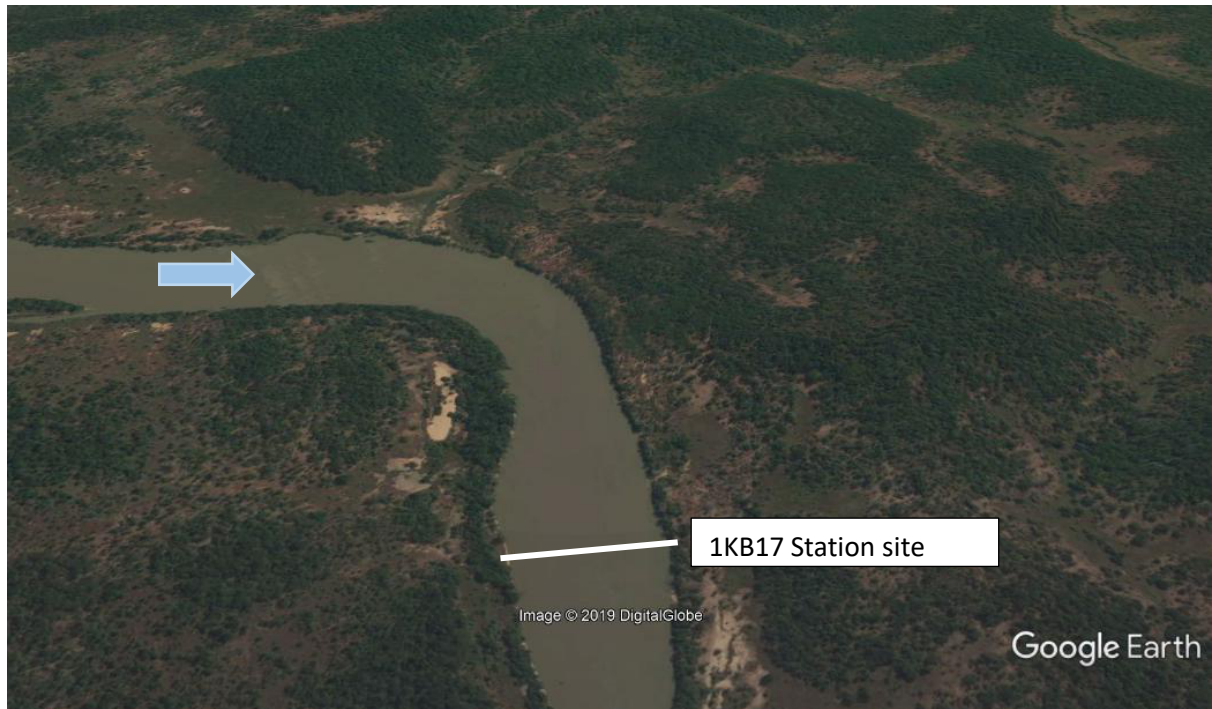


Plate 1: Google Earth image of Kilombero at Swero (1KB17) indicating sediment laden waters at very stable river banks



Plate 2: Upstream of gauge station site at Swero



Plate 3: Stable right bank (direction of flow) at Swero

4.2.5 Projected Trend of Climatic Variables

The study also considered future trends of the same hydroclimatic variables to understand how they will impact water availability in the catchment. This was considered for the period between 2021 and 2050 and as was the case for historical trend, the study considered trend in Udzungwa escarpment, Mahenge escarpment, Kilombero valley portion and the average entire catchment area. The sub-sections below discuss the results of these future results.

(i) Projected Precipitation Trend

Results of the projected trend for precipitation variable is illustrated in Fig. 13 and statistical test results presented in Table 8. According to the result, it was shown that while historical precipitation had been on an increase at a rate of 2.08 mm/yr, the future showed the opposite trend of decreasing precipitation at an average rate of 1.50 mm/yr (value of Sen's slope) for the entire catchment consideration. This agrees well with conservative recommendations by Gebrechorkos *et al.* (2019) who claimed a weak suggestions for increasing future trend. The specific results for all the four climatic zone considerations are as presented in Table 8.

In addition to that, in all the four climatic zones, the trend was interpreted to be statistically significant following the absolute value of Z statistic being greater than the P – value. This future projection was also in agreement with the other regional scale projections that show a general decrease in precipitation in the southwestern highlands at a rate ranging between 0.5 to 1mm/day for both RCP 8.5 and RCP 4.5 emission scenarios (Luhunga *et al.*, 2018). However, it is important to note that there was a great deal of uncertainty in the projected climate change in the country. This is attributable to the fact that many studies are based on GCMs climate simulations which have coarse spatial relationship to reproduce regional or local climate pattern (Jones *et al.*, 2004). Furthermore, the physical and dynamical processes important in modeling regional or sub regional climate are parameterized and insufficient within the GCMs. Their outputs are therefore useful only at a global scale but are not adequate at regional, sub regional and local scale (Luhunga *et al.*, 2018).

Table 8: Summary of statistical test results for projected precipitation variable at confidence level of 95% ($\alpha=0.05$)

N	Climatic Zone	Z	Sen's Slope	s	Var(s)	Kendal tau	P-value
1	Kilombero Valley	-0.86	-3.80	-49.00	3141.67	-0.11	0.39
2	Mahenge Escarpment	-1.43	-5.82	-81.00	3141.67	-0.19	0.15
3	Udzungwa Escarpment	-1.71	-4.10	-97.00	3141.67	-0.22	0.09
4	Kilombero Catchment	-1.50	-4.05	-85.00	3141.67	-0.20	0.13

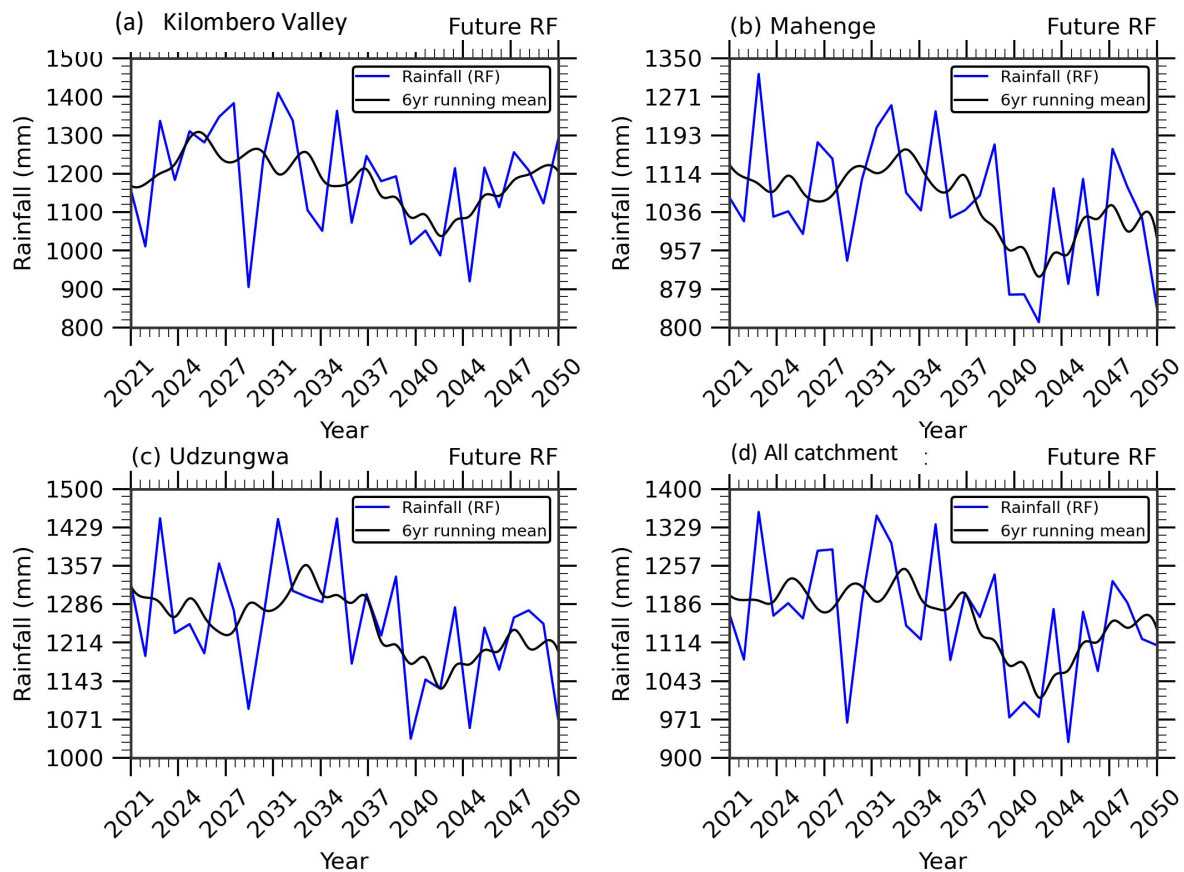


Figure 13: Projected trend of precipitation data showing a general decline of precipitation in all the four climatic zones

(ii) Projected Maximum and Minimum Temperature Trend

The statistical test results for T_{max} and T_{min} are presented in Table 9 and 10 while their graphical illustration is presented in Fig. 14 and 15, respectively. In both cases the statistical test showed that the trend was statistically significant (absolute value of Z statistic is greater than P – value) and increased slightly at a rate of $0.03^{\circ}\text{C}/\text{year}$ considering the overall Kilombero catchment results. Results for other climatic zones are presented in Table 9 and 10. These are in agreement with scholars such as Luhunga *et al.* (2018) and Borhara *et al.* (2020) who also showed a general increment of minimum and maximum temperature across the country but in south western highlands they ranged from 3.9 to 4.5°C and 1.6 to 2.2°C under RCP 8.5 and RCP 4.5 emission scenarios, respectively.

In general, projected increases in minimum and maximum temperatures will inevitably have negative impacts on socioeconomic development in the country. For instance, this increase is expected to reduce the length of growing season for some crops and are expected to encourage diseases and pest eruption (Luhunga *et al.*, 2018). For paddy in particular which is the dominant staple and cash crop in Kilombero catchment, the projected increase in temperature variable

was expected to also reduce its yields (Peng *et al.*, 2004). Furthermore, scientists have also indicated that the projected increase in temperature across the country may cause wilting and drying of plants, multiplication of pest, weeds and diseases, resulting in increased costs of crop production and crop yield losses (URT, 2003).

Table 9: Summary of statistical test results for projected T_{max} variable at confidence level of 95% ($\alpha = 0.05$)

N	Climatic Zone	Z	Sen's Slope	s	Var(s)	Kendal tau	P-value
1	Kilombero Valley	3.71	0.03	208.00	3107.33	0.48	0.00
2	Mahenge Escarpment	3.50	0.03	231.00	3108.00	0.45	0.00
3	Udzungwa Escarpment	3.91	0.03	255.00	3111.00	0.50	0.00
4	Kilombero Catchment	3.78	0.03	211.00	3082.33	0.49	0.00

Table 10: Summary of statistical test results for projected T_{min} variable at confidence level of 95% ($\alpha = 0.05$)

N	Climatic Zone	Z	Sen's Slope	s	Var(s)	Kendal tau	P-value
1	Kilombero Valley	4.89	0.03	272.00	3068.00	0.63	0.00
2	Mahenge Escarpment	4.14	0.03	231.00	3091.00	0.53	0.00
3	Udzungwa Escarpment	4.58	0.03	255.00	3075.00	0.59	0.00
4	Kilombero Catchment	4.79	0.03	265.00	3033.00	0.61	0.00

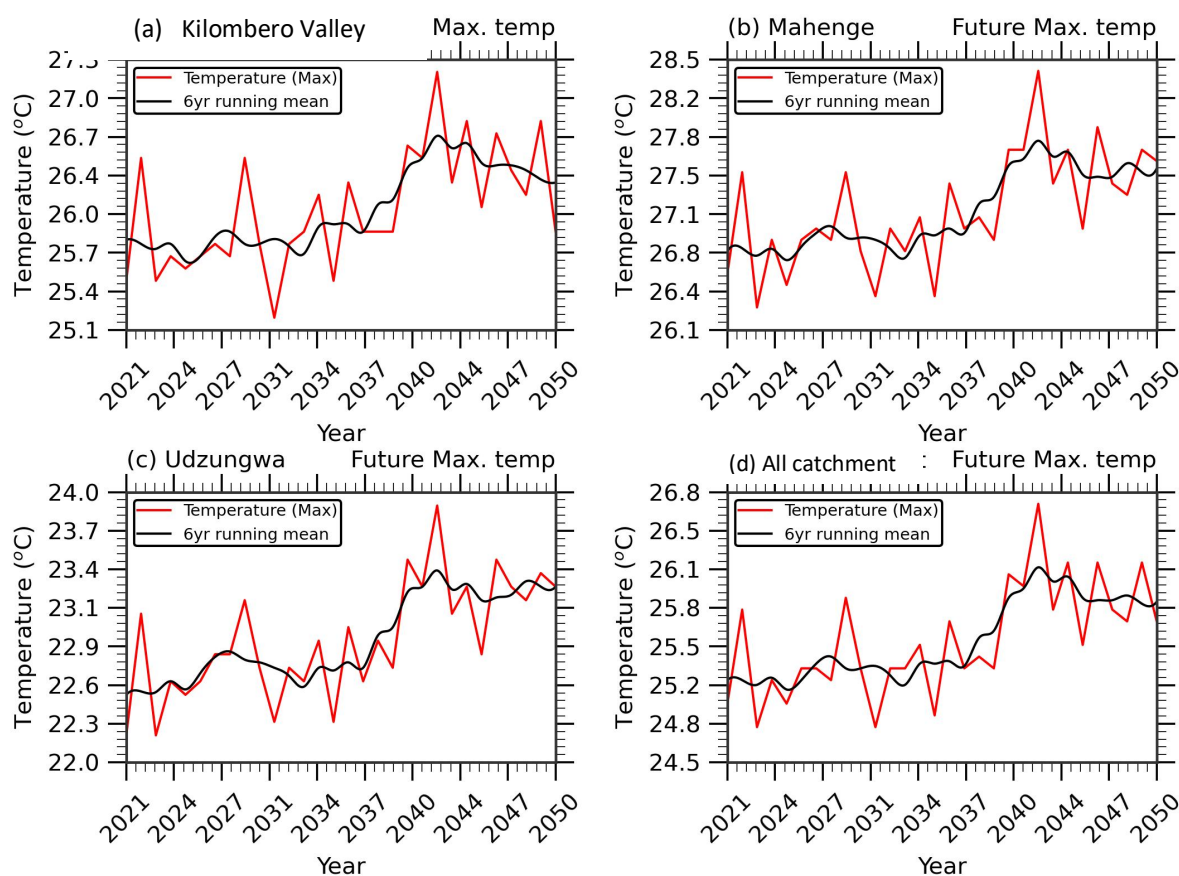


Figure 14: Projected trend of T_{max} data showing a general increasing trend in all the four climatic zones

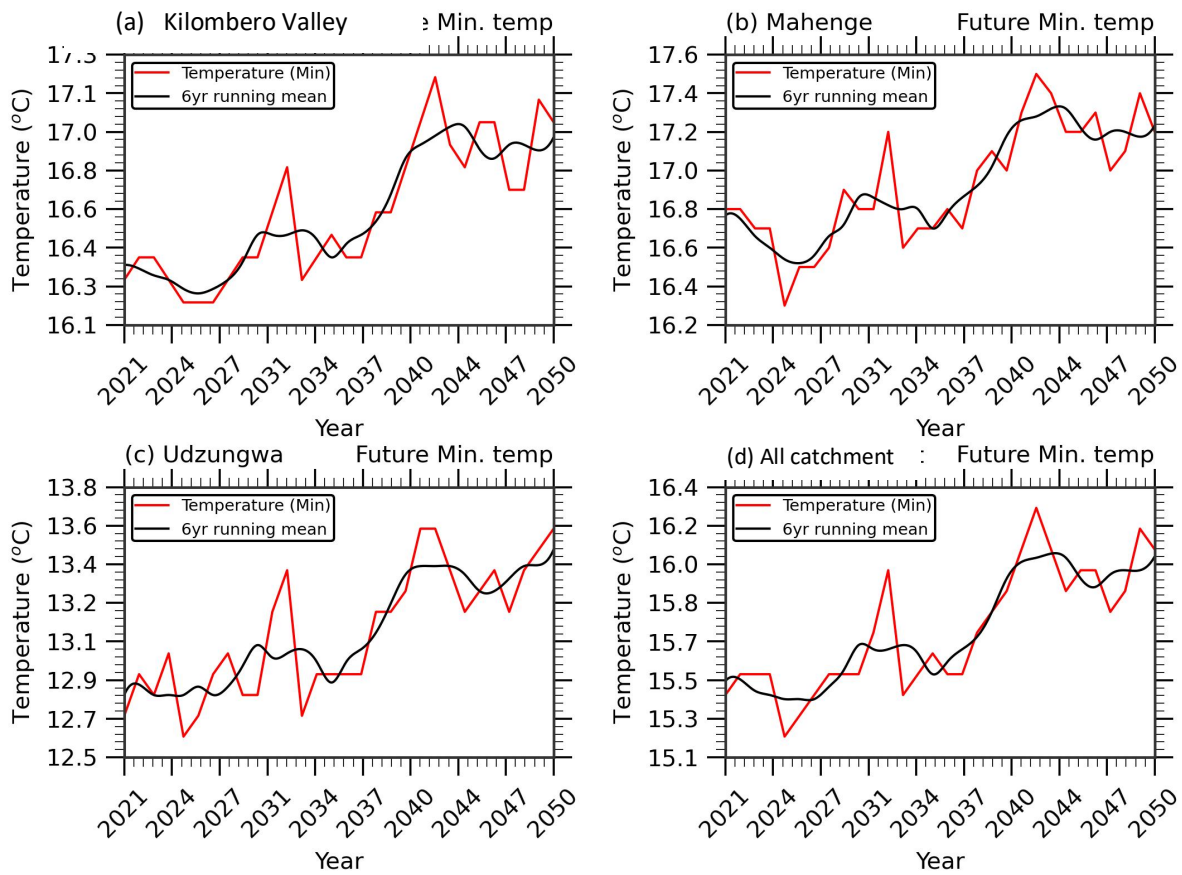


Figure 15: Projected trend of T_{min} data showing a general increasing trend in all the four climatic zones

(iii) Projected Evapotranspiration Trend

The results for statistic trend analysis for potential evapotranspiration in the different climatic zones within Kilombero Catchment are presented in Table 11 and Fig. 16. The results showed an increasing trend in all cases (positive Sen’s slope) and this trend is statistically significant (absolute value of Z statistic greater than P – value). Interpretation of the historical and project data showed that temperature is increasing at a relatively same rate. However, precipitation and potential evapotranspiration were changing and presented an inverse proportional relationship. This can be attributed to the fact that, rainfall increases humidity in these cold and areas limited wind activities (Alfayo & Uiso, 2002). With a huge Selous forest eastwards which is about 50 000 km² (Jaeger *et al.*, 2014), it was interpreted that, forests cause weaker winds reaching the catchment and hence manifest saturated water vapor in the air that in turn causes low evapotranspiration.

Table 11: Summary of statistical test results for projected PET variable at confidence level of 95% ($\alpha = 0.05$)

N	Climatic Zone	Z	Sen's Slope	s	Var(s)	Kendal tau	P-value
1	Kilombero Valley	1.39	2.23	79.00	3141.67	0.18	0.16
2	Mahenge Escarpment	2.14	2.72	231.00	3141.67	0.28	0.03
3	Udzungwa Escarpment	1.96	2.13	255.00	3141.67	0.26	0.05
4	Kilombero Catchment	2.07	2.29	117.00	3141.67	0.27	0.04

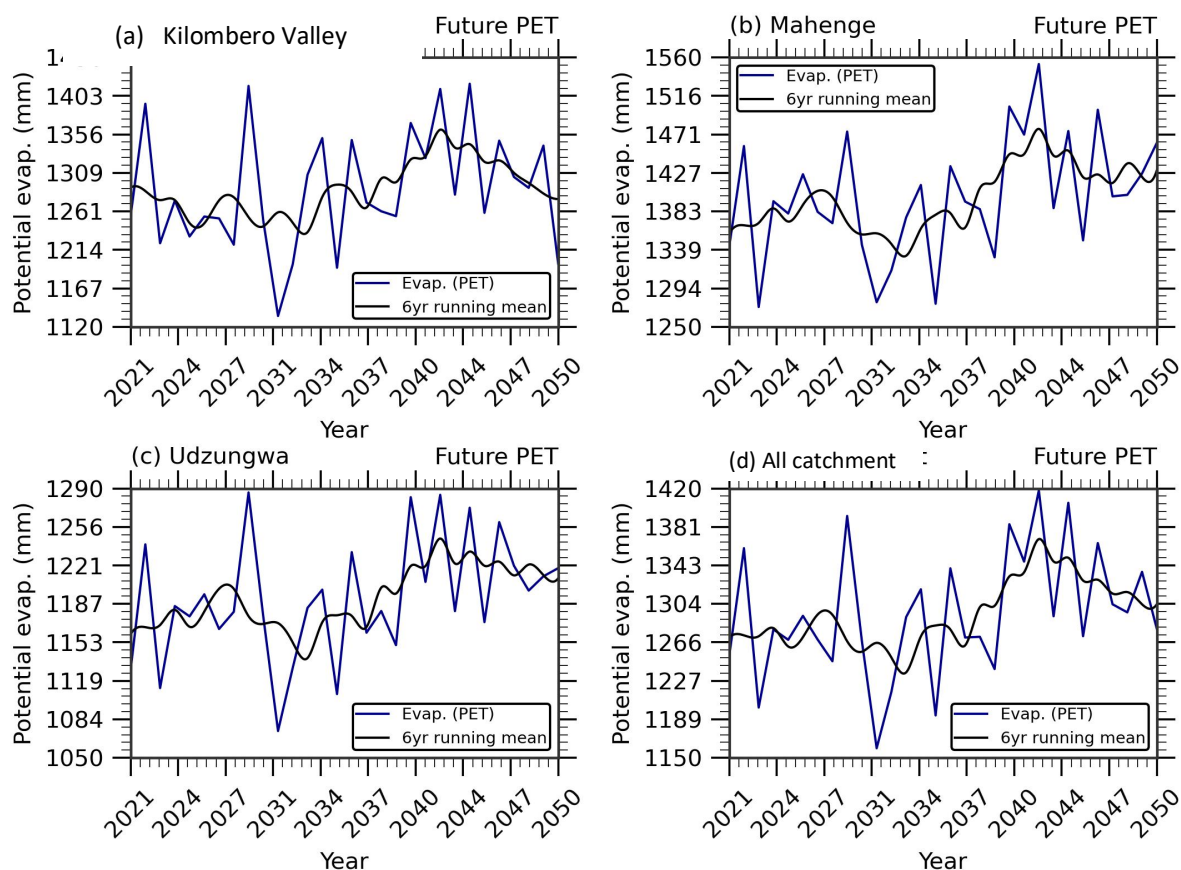


Figure 16: Projected trend of PET data showing a general increasing trend in all the four climatic zones

4.2.6 Land-Use/Cover Changes

(i) Results for Accuracy Assessment

Table 12 presents a summary of the producers' accuracy (PA), users' accuracy (UA), overall accuracies and kappa statistics of the many LULC classes in the Kilombero River Catchment maps for different periods. The overall land use/cover classification accuracy for the years 1991, 2001, 2011 and 2021 is 92.01%, 91.74%, 91.96% and 92.44%, respectively, with the general kappa statistics of 0.90 for all year. The accuracy result showed that the classification accuracy is above 0.8, indicating high agreement, which is acceptable for the classification, detection, and prediction of land use/cover in the Kilombero River Catchment.

Table 12: Accuracy assessment for 1991, 2001, 2011 and 2021 classification

Land Use/Cover	1991		2001		2011		2021	
	PA	UA	PA	UA	PA	UA	PA	UA
Forest	90.88	79.12	90.88	79.88	90.36	86.94	87.74	81.38
Woodland	82.10	73.70	82.10	73.70	86.45	72.88	81.86	78.06
Bushland	88.20	96.03	88.20	96.03	88.80	95.23	92.21	96.93
Grassland	95.93	99.87	95.93	99.87	95.93	99.87	96.06	95.88
Water	94.89	89.56	94.89	94.09	97.87	99.57	97.87	100.00
Wetland	99.06	99.66	99.69	99.66	99.08	99.69	99.64	100.00
Cultivated land	99.34	95.45	95.55	93.36	88.80	96.54	88.91	94.88
Built-up area	99.56	100.00	90.63	84.65	99.56	68.36	99.14	68.69
Overall Accuracy	92.01		91.74		91.96		92.44	
Kappa	0.90		0.90		0.09		0.90	

(ii) Analysis of Land-Use/Land-Cover Change Pattern

The areas under different land use/land cover (LULC) types and percentage are given in Table 13. The LULC percentage graph and maps for the years 1991, 2001, 2011 and 2021 are presented in Fig. 17 (This illustrates the increasing human activities at the detriment of sources of ecosystem services) and 18 (Illustrating the declining pristine nature of the catchment owing to anthropogenic causes), respectively.

According to the assessment results, the area was transformed from forest LULC which was leading as the dominant LULC in the first two decades i.e., an area of 1 192 996 Ha in 1991 and 1 177 109 Ha in 2001. This formed almost a third of the total catchment area i.e., 29.55% and 29.16%, respectively. The same LULC which is key for regulation of local climate (Wolff *et al.*, 2018) took the 3rd position in terms of land mass i.e., 20.92% and 19% in the year 2011 and 2021, respectively. These transformations seem to have been caused by the expanding cultivated land which grew consistently over the years but maintained the same fourth position in terms of land mass until 2021 when it took second place. This is a linear growth from 7.96%, 8.43%, 19.23% and 24.29% in 1991, 2001, 2011 and 2021, respectively.

Because the growth of cultivated land targeted moist and fertile areas, river buffers and the wetland were an automatic victim. These areas shrunk almost by half between 1991 and 2021 with area under wetland shrunk from 7.48% of the total area to 4.86% and the area occupied by water bodies from 0.46% to 0.26%. While these expansions in farms contributed immensely in food security and peoples livelihood (Buck & Milder, 2012; Kangalawe & Liwenga, 2005; Milder *et al.*, 2013), they also contributed to negative impacts to sediment generation and water yield from this catchment (Munishi & Jewitt, 2019; Senkondo *et al.*, 2019; Thonfeld *et al.*, 2020).

Table 13: Historical Land Use/Cover Spatial Coverage showing the area and percentage of each category and the comparable increase in landmass under human activities vs sources of ecosystem services e.g. forests and wetlands

Year	Land Use/Cover							
	1991		2001		2011		2021	
Unit	Ha	%	Ha	%	Ha	%	Ha	%
Forest	1 192 996	29.55	1 177 109	29.16	844 527	20.92	766 835	19.00
Woodland	1 141 382	28.27	1 121 891	27.79	1 114 763	27.61	741 798	18.37
Bushland	1 019 128	25.25	1 029 224	25.50	972 794	24.10	1 253 491	31.05
Grassland	34 067	0.84	33 500	0.83	44 310	1.10	67 614	1.67
Water	18 641	0.46	15 095	0.37	11 578	0.29	10 419	0.26
Wetland	302 098	7.48	311 029	7.70	256 250	6.35	196 912	4.88
Cultivated	321 188	7.96	340 472	8.43	776 181	19.23	980 534	24.29
Built up	7437	0.18	8615	0.21	16 531	0.41	19 331	0.48
Total	4 036 935	100	4 036 935	100	4 036 935	100	4 036 935	100

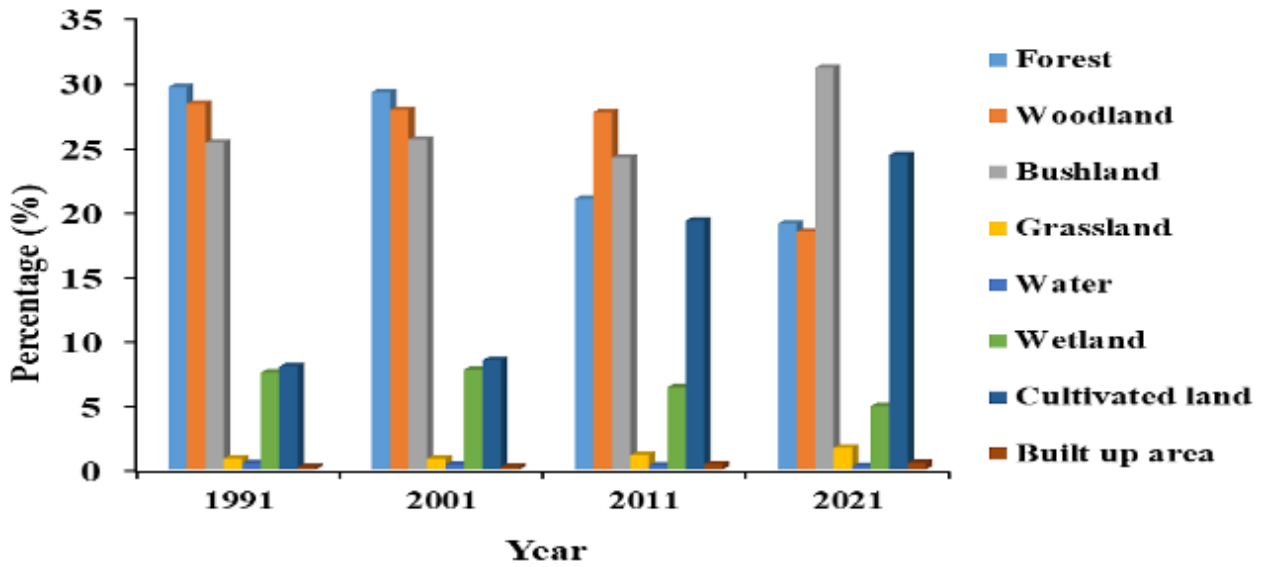


Figure 17: The LU/LC graphs showing relative percentage coverage for each category

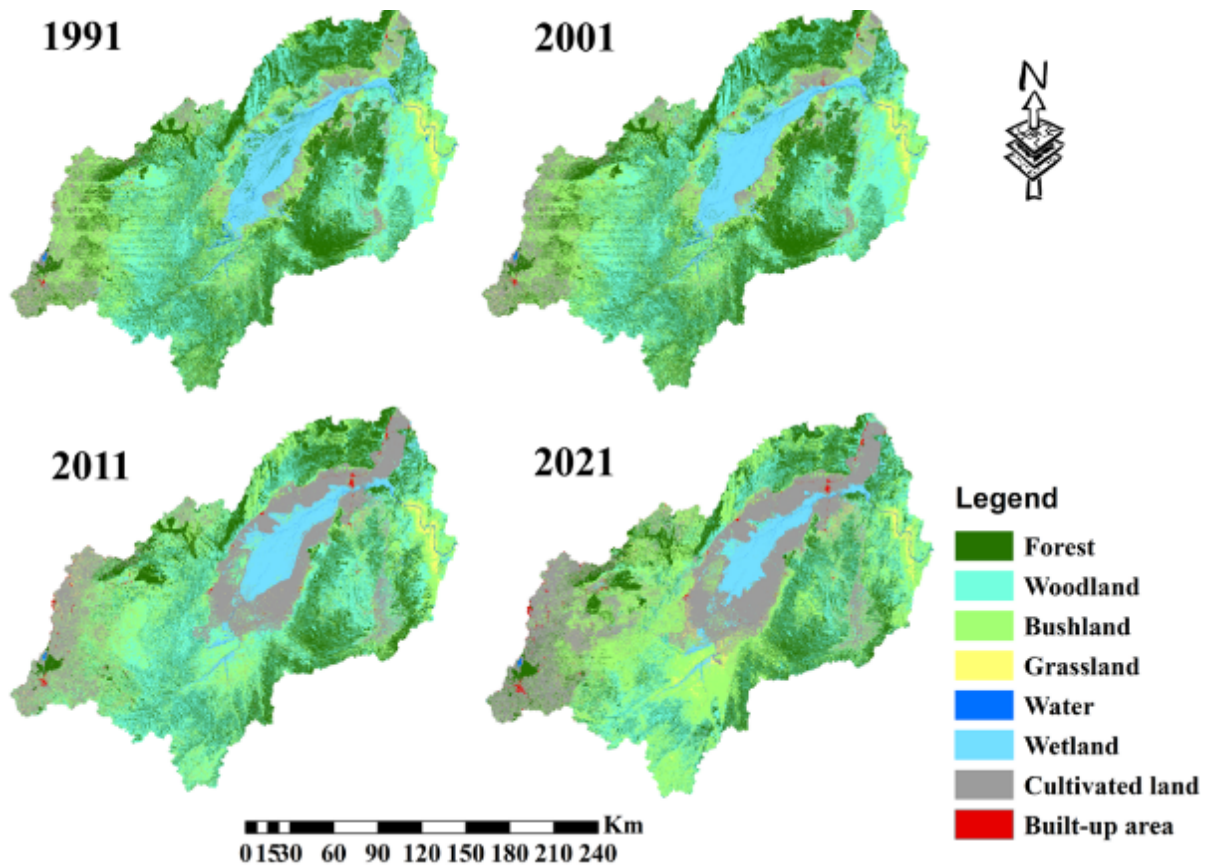


Figure 18: Spatial display of historical changes in LULC for KRC

The changes in LULC for the study period of 1991 - 2001, 2001 - 2011, and 2011 - 2021 are given in Table 14 and illustrated in Fig. 19. During these study periods, the major decline in land mass was experienced in forests, woodland and wetland whereas maximum increase has been registered in cultivated lands, Grassland and Buildup areas. This was attributed to expansion in agricultural activities which also pulled in permanent settlements. Although there

was a steady increase in land mass under cultivation across the board, the period between 2001 and 2011 experienced the most significant jump. This could be attributed to three major government strategies, i.e., the Big Results Now (BRN) of 2013, the Kilimo Kwanza Initiative (KKI), translated as the prioritization of agriculture in June 2009, and the establishment of the southern agricultural growth corridor (SAGCOT) by 2010. All of them are based on the need to link the local peasantry farmers with agribusiness actors across the corridor (including Kilombero, which forms the most consequential cluster).

Furthermore, the privatization and establishment of big sugarcane plantation, which Kilombero Sugar Company Limited (KSCL) took over in 1998, expanded significantly around 2005–2006 following their initiative to build the Kidatu Bridge and associated road improvements, which by itself also spearheaded agriculture expansion in the catchment. In addition, Kilombero Plantations Limited (KPL) was privatized and expanded paddy farming activities by 2008–2010. Both plantations introduced and supported out-grower farmers' schemes, which expanded just as much as the plantations themselves. However, the implementation of the enacted Water Resources Management Act No. 11 of 2009 and the establishment of a record number of water users' associations (WUAs) in the catchment saw the decline of cultivated land within the protected wetland and river buffer. This increased bushland (abandoned farms) and reduced the decline of areas occupied by water. Wetlands continued to decline since abandoned farms (bushlands) were yet to rejuvenate into proper wetlands. The specific rate of change and percentages for each year for all LULC in the study periods are also presented in Table 14.

Table 14: The LU/LC area changed, percentage change and annual rate of change

Year	1991 - 2001			2001 - 2011			2011 - 2021			1991 - 2021		
Unit	Ha	%	Ha/Yr	Ha	%	Ha/Yr	Ha	%	Ha/Yr	Ha	%	Ha/Yr
Forest	-15 887	-1.3	-1589	-332 582	-28.3	-33 258	-77 692	-9.2	-7769	-426 161	-35.7	-14 205
Woodland	-19 491	-1.7	-1949	-7128	-0.6	-713	-372 965	-33.5	-37 297	-399 584	-35	-13 319
Bushland	10 096	1.0	1010	-56 430	-5.5	-5643	280 697	28.9	28 070	234 363	23	7812
Grassland	-567	-1.7	-57	10 810	32.3	1081	23 304	52.6	2330	33 547	98.5	1118
Water	-3546	-19	-355	-3517	-23.3	-352	-1159	-10	-116	-8222	-44.1	-274
Wetland	8931	3	893	-54 779	-17.6	-5478	-59 338	-23.2	-5934	-105 186	-34.8	-3506
Cultivated	19 284	6.0	1928	435 709	128	43 571	204 353	26.3	20 435	659 346	205.3	21 978
Built up	1178	15.8	118	7916	91.9	792	2800	16.9	280	11894	159.9	396

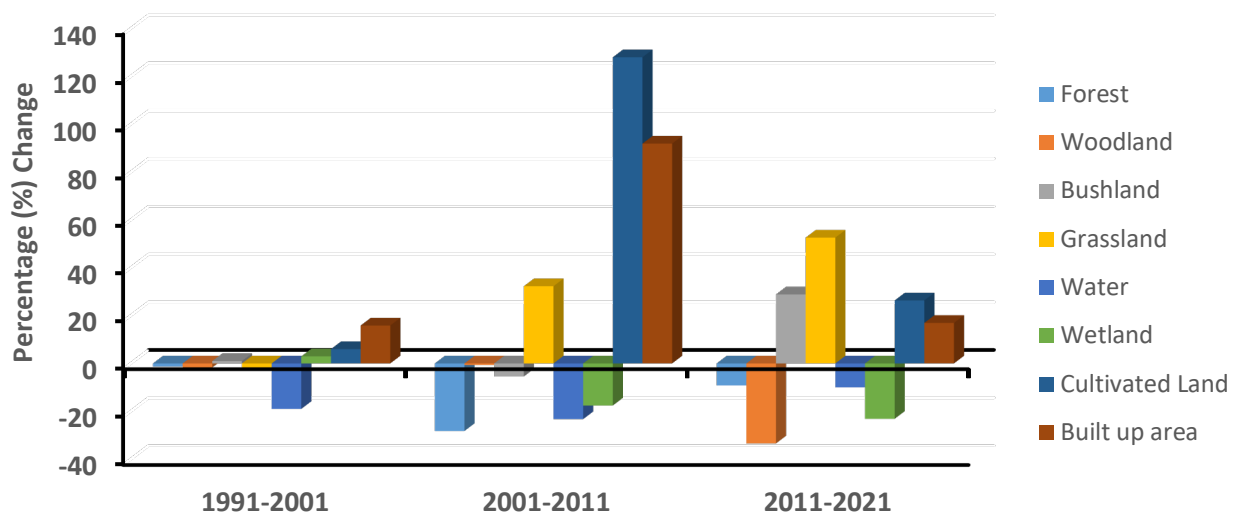


Figure 19: The ULC changes for time span 1991 – 2001; 2001 – 2011 and 2011 – 2021 showing cultivate land and settlements increased significantly between 2001 – 2011 due to government policy on expanding agriculture

(iii) Transformation of Different LULC

Table 15 to Table 18 indicate the areas changed based on the change matrix cross-tabulation from 1991 to 2021 whereby land use/land cover class is compared to one another. For the study period between 1991 and 2021 (Table 15), among all the land use/land cover types, forest experienced a maximum net loss (-426 123 Ha), followed by woodland (-399 615 Ha), wetland (105 187 Ha), and water (-8220 Ha). On the other hand, cultivated land experienced maximum net gain (659 346 Ha) followed by bushland (234 373 Ha), grassland (33 547 Ha) and built-up area (11 879 Ha). During this same study period (1991 - 2021), there were portions of LULC that never changed to others. As presented in the left–right diagonal line in Table 15, the chronology was led by forest (528 049 Ha) followed by bushland (442 391 Ha), woodland (398 012 Ha), cultivated land (241 550 Ha), wetland (170 230 Ha), grassland (16 796 Ha), water (8 596 Ha) and built up area (5237 Ha).

Results for other study periods i.e., 1991 - 2001, 2001 - 2011 and 2011 – 2021 are summarized in Table 16, 17 and 18, respectively. As stated above, there was a clear linkage between the expansion of farms and settlements to the loss of forest LULC. Owing to the implementation of the government strategies on agriculture between 2005 and 2015, most expansion happened in 2011 – 2021 study period as illustrated in Table 19. These included the Kilimo Kwanza Initiative (KKI), translated as the prioritization of agriculture launched in June 2009 and the Big Results Now (BRN) of 2013, which saw among others, the establishment of the southern

agricultural growth corridor (SAGCOT) by 2010. Previously there had been similar policies that enhanced agricultural production in the country. These programs have had similar impact on natural ecosystems such as wetlands and forests which were natural casualties. These policies based on ad hoc decisions made from the onset of Tanzania's independence in 1961 where a series of major economic, social and political transformation programmes were implemented. All these were meant to liberate the country from abject poverty and improve citizens' welfare. The agricultural sector was central to these programmes whereby many policies (slogans) to mobilize farmers were introduced from time to time (Table 15). The best example is Siasa ni Kilimo (Politics is Agriculture) declared by Mwalimu Nyerere in 1972 in Iringa to mark the nation's dedication to agriculture as the central pillar of economic growth. Within the same context, Kilimo cha Kufa na Kupona ('Do or Die' Agriculture) was introduced in 1983 in Moshi. And hardly a year after, Kilimo cha Umwagiliaji (Irrigation Agriculture) was announced in 1984 (Limbu, 1995). Several of the initiatives implemented in the mid-1970s were basically government attempts to address the effects of long droughts experienced in 1973-74. Yet, while the previous government policy initiatives were responding to natural and manmade calamities (Limbu, 1995), recent policies are strongly influenced by global processes that aim to shift agriculture towards an industrial scale, responding to global market demands. This then means that forest, wetlands and other natural resources are yet to be out of the woods in respect of encroachments fostered by these local and global demands. To reverse this experience, it is imperative to institute landuse plans and water resources management plans that are luckily prominent in respective legislations.

Table 15: Selected Tanzania's agricultural sector strategies from independence

N	Year	Policy/Initiative	Author	Coordinator	Financier	Main Focus
1	1972	Siasa ni Kilimo (Politics is Agriculture)	Ministry of Agriculture (MoA)	MoA	Government of Tanzania (GoT)	Smallholder
2	1983	Kilimo cha Kufa na Kuona ('Do or Die' Agriculture)	MoA	MoA	GoT	Smallholder
3	2006 – 27	Agricultural Sector Development Programme	Ministry of Agriculture, Food Security and Cooperatives (MAFSC)	MAFSC	GoT, Donor Baket Fund	Smallholder production, irrigation
4	2009	Kilimo Kwanza (Agriculture First)	Tanzania National Business Council (TNBC)	PMO-RALG	GoT, donors, private sector	Commercial agriculture
5	2010	South Agriculture Growth Corridor (SAGCOT)	MAFSC	SAGCOT Center	GoT, donors. (G8), private sector	Commercial agriculture, smallholder
6	2012 – 17	Tanzania Agriculture & Food Security Investment Plan	CAADP*/MAFSC	MAFSC	GoT, donors, private sector, philanthropies	Smallholder production, Food security
7	2012	Big Results Now	Presidential Delivery Bureau	Presidential Delivery Bureau	GoT, Donors, Private Sector	Commercial agriculture, smallholder
8	2013	National Agriculture Policy	MAFSC	MAFSC	GoT, Donors	Green Revolution

Cooksey (2014) and Limbu (1995)

Table 16: Land use/land cover detection matrix during the period 1991 – 2021

Changing from:1991	Area Change to 2021									Net change (Ha)
	FRST	FRSD	RNGB	RNGE	WATR	WETN	CULT	BULT	LOSS	
FRST	528 049	234 022	275 309	8531	832	15 163	130 260	829	664 946	-426 123
FRSD	158 889	1 991	463 685	10 166	302	3645	106 025	660	743 372	-399 615
RNGB	61 785	92 919	442 391	24 808	148	2193	390 911	3,973	576 737	234 373
RNGE	155	316	11 654	16 796	7	10	5071	58	17 271	33 547
WATR	809	1714	2319	196	8596	3288	1690	27	10 043	-8 220
WETN	838	8053	17 284	1021	414	170 230	104 073	184	131 867	-105 187
CULT	16 216	6498	40 264	5812	120	2381	241 550	8347	79 638	659 346
BULT	131	235	595	284	0	0	954	5237	2 199	11879
GAIN	238 823	343 757	811 110	50 818	1823	26 680	738 984	14 078	1 561 127	

Note: FRST= Forest; FRSD= Woodland; RNGB= Bushland; RNGE= Grassland; WATR= Water; WETN= Wetland; CULT= Cultivated land; BULT= Built up area. The bold numbers on the diagonal represent unchanged land use/land cover proportions from 1991 to 2021 while the others are the areas changed from one class to another

Table 17: Land use/land cover detection matrix during the period 1991 – 2001

Changing from:1991	Area Change to 2001									Net change (Ha)
	FRST	FRSD	RNGB	RNGE	WATR	WETN	CULT	BULT	LOSS	
FRST	1 165 330	3331	12 672	0	0	10 815	835	11	27 664	-15 886
FRSD	3346	1 114 670	23 056	0	0	0	107	202	26 711	-19 491
RNGB	7081	3603	987 618	174	8	31	20,141	473	31 511	10 095
RNGE	2	0	172	33 317	0	0	577	0	751	-568
WATR	1,210	197	446	9	15 076	1551	131	21	3565	-3545
WETN	106	89	2289	0	12	298 632	969	0	3465	8932
CULT	31	0	2726	0	0	0	317 416	1 015	3772	19 285
BULT	2	0	245	0	0	0	297	6893	544	1178
GAIN	11 778	7220	41 606	183	20	12 397	23 057	1722	70 319	

Note: FRST= Forest; FRSD= Woodland; RNGB= Bushland; RNGE= Grassland; WATR= Water; WETN= Wetland; CULT= Cultivated land; BULT= Built up area. The bold numbers on the diagonal represent unchanged land use/land cover proportions from 1991 to 2001 while the others are the areas changed from one class to another

Table 18: Land use/land cover detection matrix during the period 2001 – 2011

Changing from:2001	Area Change to 2011									Net change (Ha)
	FRST	FRSD	RNGB	RNGE	WATR	WETN	CULT	BULT	LOSS	
FRST	742 548	242 722	102 891	493	904	9508	77 577	457	434 552	-332 574
FRSD	80 626	830 707	151 851	589	226	2437	55 434	20	291 183	-7147
RNGB	15 965	33 574	684 154	574	7	1776	292 367	826	345 089	-56 430
RNGE	0	0	0	33 500	0	0	0	0	0	10 809
WATR	1012	389	966	155	10 058	2117	396	1	5036	-3516
WETN	251	2248	11 130	486	319	234 274	62 151	170	76 755	-54 778
CULT	4124	5103	21 821	8512	64	6139	288 257	6,441	52 204	435 721
BULT	0	0	0	0	0	0	0	8,615	0	7915
GAIN	101 978	284 036	288 659	10 809	1520	21 977	487 925	7915	770 267	

Note: FRST= Forest; FRSD= Woodland; RNGB= Bushland; RNGE= Grassland; WATR= Water; WETN= Wetland; CULT= Cultivated land; BULT= Built up area. The bold numbers on the diagonal represent unchanged land use/land cover proportions from 2001 to 2011 while the others are the areas changed from one class to another

Table 19: Land use/land cover detection matrix during the period 2011 – 2021

Changing from:2011	Area Change to 2021									Net change (Ha)
	FRST	FRSD	RNGB	RNGE	WATR	WETN	CULT	BULT	LOSS	
FRST	558 295	135 303	130 717	2172	263	244	17 224	234	286 157	-77 686
FRSD	118 408	460 304	456 918	13 006	200	2219	62 935	604	654 290	-372 978
RNGB	67 442	132 180	592 540	27 325	255	3874	147 745	1776	380 597	280 699
RNGE	350	351	12 452	17 439	12	16	13 550	132	26 863	23 305
WATR	307	895	660	26	9112	194	383	1	2466	-1160
WETN	693	5425	10 667	913	506	189 978	48 062	2	66 268	-59 339
CULT	21 094	6832	48 931	6257	69	382	688 477	4054	87 619	204 374
BULT	177	326	951	469	1	0	2 094	12 511	4018	2785
GAIN	208 471	281 312	661 296	50168	1306	6929	291 993	6803	1 222 121	

Note: FRST= Forest; FRSD= Woodland; RNGB= Bushland; RNGE= Grassland; WATR= Water; WETN= Wetland; CULT= Cultivated land; BULT= Built up area. The bold numbers on the diagonal represent unchanged land use/land cover proportions from 2011 to 2021 while the others are the areas changed from one class to another.

(iv) Future LULC Simulation for 2031 and 2041

The validation target, kappa index of agreement (KIA) was used for the 2021 land use/land cover predictions, which were acceptable to both the actual and the predicted land use/land cover. All the kappa results showed an acceptable standard greater than 80% which confirmed that the prediction accuracy was reasonable for future land use/land cover prediction. The kappa statistics were as follows: K_{no} is 0.93, $K_{location}$ is 0.95, K_{strata} is 0.95, and $K_{standard}$ is 0.91. The corrected percentage for each type of land use/land cover was over 90%, so the model was satisfactory for making predictions for 2031 and 2041, respectively. The predicted areas of land under different land use/land cover types and percentages are given in Table 20. The respective land use/land cover for this projected period are presented in Fig. 20 and 21.

Figure 20 shows that land use/land cover for projected year 2031 will be dominated by bushland (1 309 248 Ha) followed by cultivated land (1 120 396 Ha), forest (685 239 Ha), woodland (657 047 Ha), wetland (133 897 Ha), grassland (97 030 Ha), built up area (25 918 Ha) and water (8159 Ha). For the projected year 2041, land use/land cover will be dominated by bushland (1 364 920 Ha) followed by cultivated land (1 260 186 Ha), forest (603 307 Ha), woodland (571 806 Ha), grassland (126 654 Ha), wetland (71 291 Ha), built up area (32 742 Ha) and water (6028 Ha). In these areas with tropical climates receiving good rain, it is important to note that bushlands are essentially abandoned farms due to either implementation of conservation initiatives e.g., formulation of water user's associations (WUAs) or flooded farms. That said, results still show the key role that agriculture plays in shaping the future LULC for Kilombero river catchment (KRC).

The implementation of a highway in this area will spur more economic development with agriculture at the core of it. It will be imperative to associate conservation agriculture and other initiatives if the catchment and other downstream users are to be safeguarded. Tanzania has already experiences losses and impairment to some of the critical natural infrastructure due to agricultural activities e.g., the shrinking of the Ihefu wetland linked to drying of Great Ruaha and Kirua swamp that is linked to the declining flows of Pangani River (Kashaigili, 2008; Notter *et al.*, 2013).

Table 20: The LULC for 2021, 2031 and 2041 showing the area and percentage of each category illustrating declining sources of ecosystem services

Year	2021		2031		2041	
Unit	Ha	%	Ha	%	Ha	%
Forest	766 835	19.00	685 239	16.98	603 307	14.95
Woodland	741 798	18.37	657 047	16.27	571 806	14.16
Bushland	1 253 491	31.05	1 309 248	32.44	1 364 920	33.81
Grassland	67 614	1.67	97 030	2.40	126 654	3.14
Water	10 419	0.26	8 159	0.20	6028	0.15
Wetland	196 912	4.88	133 897	3.32	71 291	1.77
Cultivated land	980 534	24.29	1 120 396	27.76	1 260 186	31.22
Built up area	19 331	0.48	25 918	0.64	32 742	0.81
Total	4 036 935	100	4 036 935	100	4 036 935	100

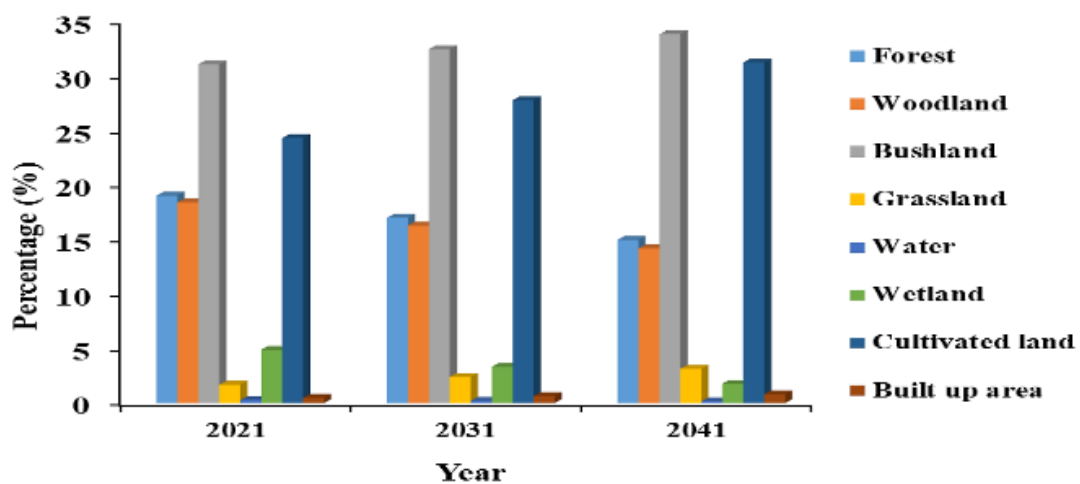


Figure 20: The LULC graph for 2021 and projected 2031 and 2041 showing farms are increasing compared to decreasing forests and water bodies (including wetlands)

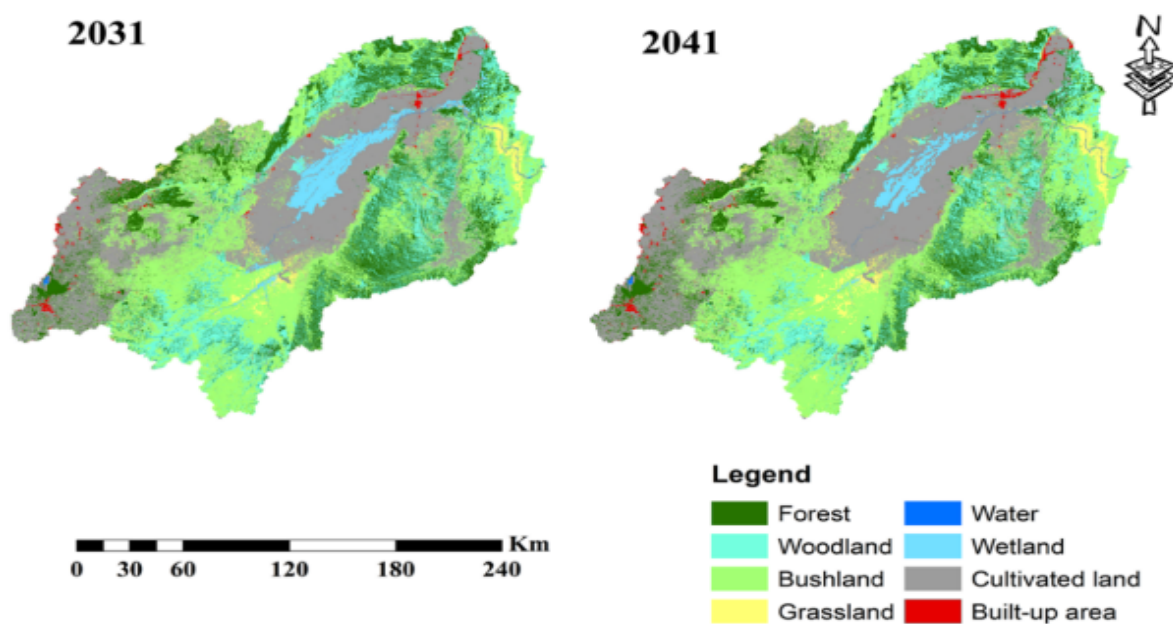


Figure 21: Projected LULC maps for 2031 and 2041 at Kilombero River Catchment showing a significant decrease of wetlands which are encroached by farms

The projected changes in land use/land cover for the period 2021 – 2031 and 2031 - 2041 are given in Table 21 and illustrated in Fig. 22. It is expected that from 2021 - 2031, woodland will experience a maximum decreased by 84 751 Ha followed by forest (81 596 Ha), wetland (63 015 Ha) and water (2260 Ha) while maximum increase will be observed on cultivated land (139 862 Ha) followed by bushland (55 757 Ha), grassland (29 416 Ha) and built-up area 6587 Ha). The maximum annual decrease will be expected on woodland (8475 Ha) followed by forest (8160 Ha), wetland (6302 Ha) and water (226 Ha) while the maximum annually increase is expected on cultivated land (13 986 Ha) followed by bushland (5576 Ha), grassland (2942 Ha) and built-up area (659 Ha).

Moreover, the projected changes for the period 2031 – 2041 maximum decrease is expected on woodland (85 241 Ha) followed by forest (81 931 Ha), wetland (62 606 Ha) and water (2131 Ha) while maximum increase is expected on cultivated land (13 979 Ha) followed by bushland (55 672 Ha), grassland (29 624 Ha) and built-up area (6824 Ha). The maximum annual decrease is expected on woodland (8524 Ha) followed by forest (8193 Ha), wetland (6261 Ha) while maximum annually increase is expected on cultivated land (13 979 Ha) followed by bushland (5567 Ha), grassland (2962 Ha) and built up are (682 Ha).

As is reported in historical trends, the future is dominated by human activities centered around agricultural production. Scholars such as Msofe *et al.* (2019) agree with our account of the possible drivers for this trend and have cited reasons such as the intensification of human activities especially agriculture followed by population growth, a growing market demand and price incentives for agricultural and forest products coupled with improved infrastructure and biophysical factors such as soil properties, climate variability and terrain characteristics.

Table 21: Projected land use/land cover showing the area changed, percentage change and annual rate change for 2031 and 2041

Year	2021 - 2031			2031 - 2041			
	Unit	Ha	%	Ha/Year	Ha	%	Ha/Year
Forest		-81 596	-10.64	-8160	-81 931	-11.96	-8193
Woodland		-84 751	-11.43	-8475	-85 241	-12.97	-8524
Bushland		55 757	4.45	5576	55 672	4.25	5567
Grassland		29 416	43.51	2942	29 624	30.53	2962
Water		-2260	-21.69	-226	-2 131	-26.12	-213
Wetland		-63 015	-32.00	-6302	-62 606	-46.76	-6261
Cultivated land		139 862	14.26	13 986	139 790	12.48	13979
Built up area		6587	34.08	659	6824	26.33	682

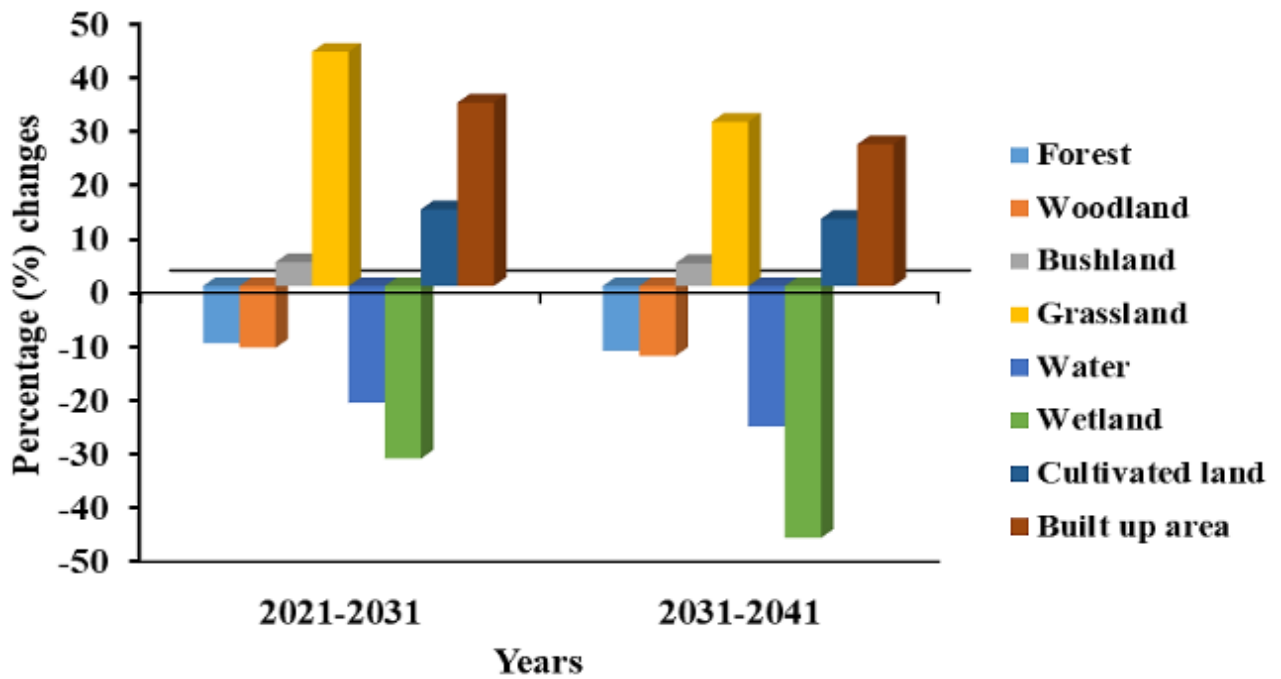


Figure 22: Projected land use/land cover changes in 2021 - 2031 and 2031 - 2041 at KRC illustrating declining situation e.g. vivid shrinkage of wetlands and water bodies

4.3 The SWAT Results for State of the Catchment

4.3.1 Sensitive Parameters

The general assessment compiled the sensitive parameters which are presented in Table 22 which gives a summary of parameters that were deemed most sensitive to flow prediction in SWAT model. The groundwater delay (GW_DELAY) which indicates the time taken in days by water to move past the lowest depth of the soil profile by percolation, was found to be the most sensitive parameter. This was followed by available water capacity of soil layer (SOL_AWC), base flow alpha factor, threshold depth of water in the shallow aquifer and surface runoff lag time.

Table 22: List of model's sensitive parameters

Rank	Parameter	Parameter definition	Fitted value
1	GW_DELAY.gw	Groundwater delay	50.368050
2	SOL_AWC	Available Water Capacity of Soil layer	0.376560
3	CN2.mgt	SCS runoff curve number	0.262836
4	ALPHA_BF.gw	Base flow alpha factor	0.866660
5	GWQWN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	1.430101
6	SURLAG	Surface runoff lag time	6.342687
7.	GW_REVAP	Threshold depth of water in the shallow aquifer for "revap" to occur	0.069006

4.3.2 Model Accuracy

As pointed out above, the accuracy assessment was performed by comparing the results between the observed and simulated stream flows. This showed a satisfactory agreement with NSE, R2, RSR and PBIAS statistical values. Table 23 presents the summary of the statistical performance of the model during calibration and validation. Assessment results showed that, during the years of calibration from 1962 to 1965, the mean observed flow was 669.81 m³/s whereas that of simulation was 672.61 m³/s. In addition, the results generated for the validation period 1966 to 1969 also showed the values of these same parameters to be 547.70 m³/s for observed flow and 649.70 m³/s for simulated flow.

The overestimation of Kilombero River discharge by SWAT model during both calibration and validation periods may be attributed to several factors rooted in model structure, parameter sensitivity, and data limitations. As indicated in Table 23, key parameters such as groundwater delay, available water capacity, and SCS runoff curve number significantly influence flow predictions. In particular, high values of groundwater delay and available water capacity may lead to delayed and exaggerated baseflow contributions, while inappropriate calibration of SCS runoff curve number can result in overestimated surface runoff.

Furthermore, the model's performance metrics, such as PBIAS values (0.4 during calibration and 18.6 during validation), suggest a systematic overprediction of discharge, particularly pronounced in the validation phase. This discrepancy may also arise from sparse or low-resolution rainfall and land-use data, which are critical inputs for hydrological modeling in large catchments like Kilombero. Studies such as Valencia *et al.* (2024) and Gurara *et al.* (2023) have shown that in tropical basins, uncertainties in input data especially regarding rainfall distribution, evapotranspiration estimates, and groundwater parameters can lead to significant model bias. Additionally, historical streamflow records in many African basins often suffer from temporal gaps and inaccuracies, which further complicate calibration efforts (Thiaw, 2025).

Table 23: Evaluation Statistics for calibration and validation for Kilombero at Swero 1KB17

Calibration				Validation				Calibration		Validation	
NSE	R ²	RSR	PBIAS	NSE	R ²	RSR	PBIAS	Ob-flow (m ³ /s)	Sim-flow (m ³ /s)	Ob-flow (m ³ /s)	Sim-flow (m ³ /s)
0.65	0.66	0.60	0.4	0.42	0.46	0.76	18.6	669.81	672.81	547.70	649.70

Ob-flow is Observed flow Sim-flow is Simulated flow

Fig. 23 and 24 show the flow hydrograph for the period during calibration and validation respectively. In addition, Fig. 25 represent the comparison of measured and simulated stream flow during model calibration and validation.

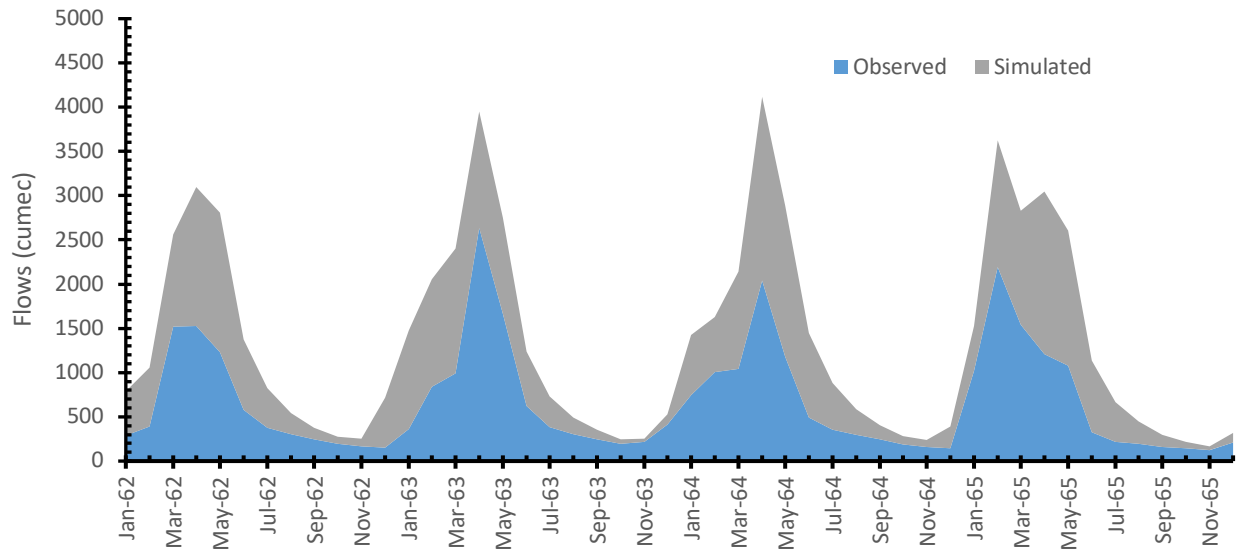


Figure 23: Overestimating simulation owing to limited data in this catchment

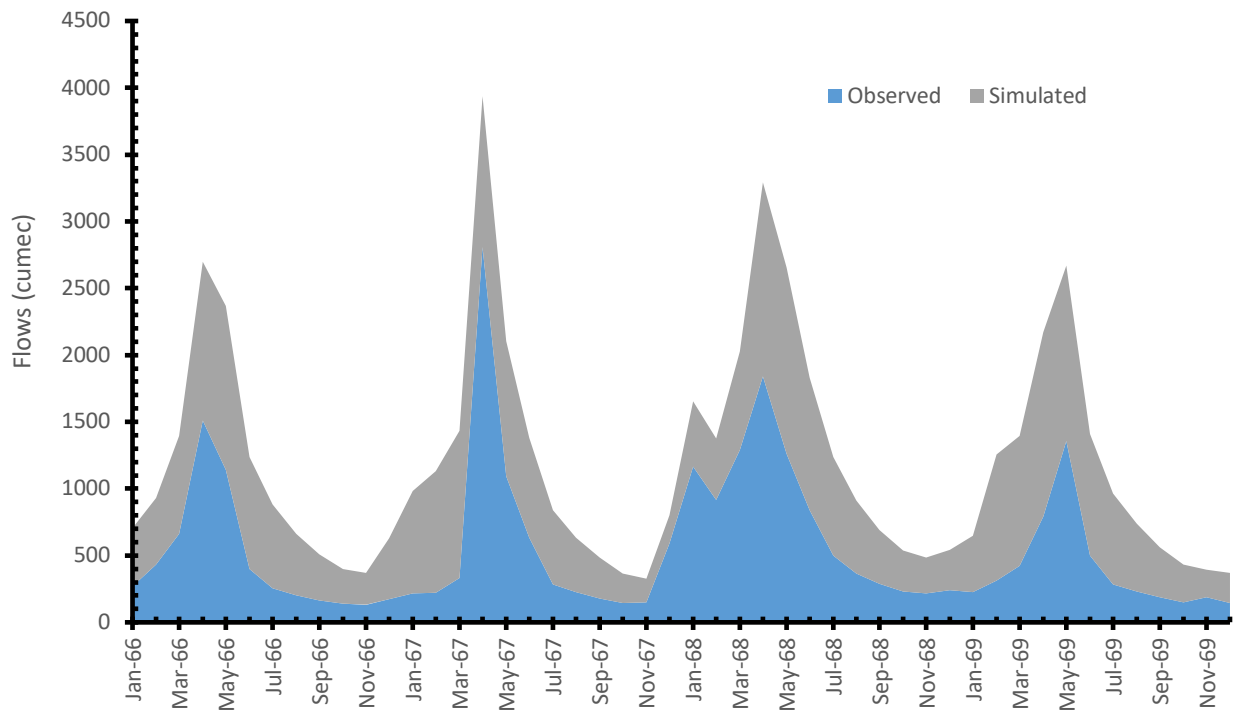


Figure 24: Measured and simulated flow data for validation period

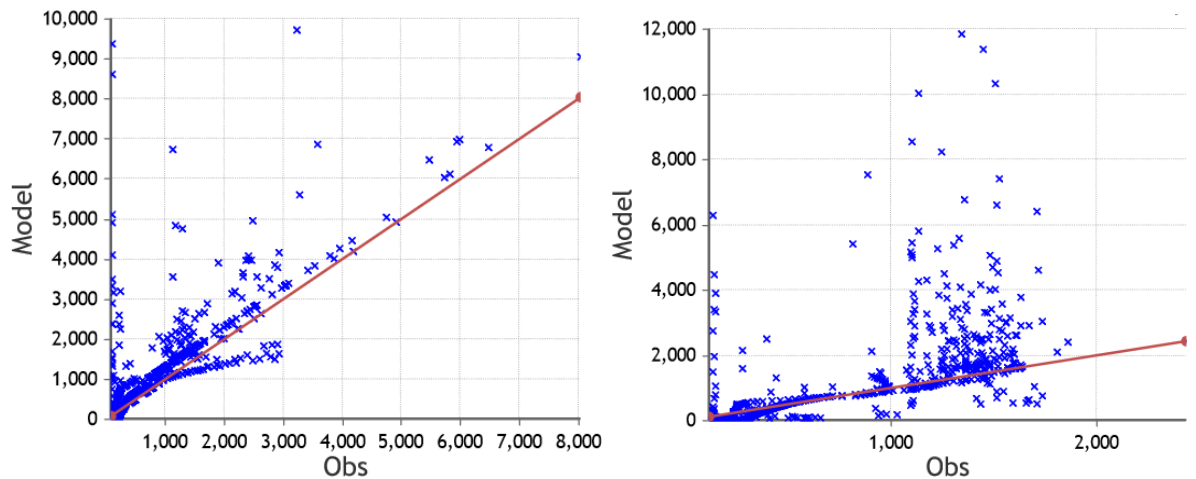


Figure 25: Comparison of measured vs simulated stream flow for model calibration (a) and validation (b)

4.3.3 Impacts of LULC Change on Water and Sediment Yields

The results for the historical annual averages of the hydrological parameters for the study area are summarized in Table 24. These averages were calculated under changing LULC to build an understanding of how LULC has contributed to hydrological changes in terms of water quality (sediment load) and quantity. The message drawn from the model results for the years between 1991 and 2021 as presented in Table 24 was that, the change of LULC contributed to the increased average annual surface runoff by 38.66 mm and decreased average annual groundwater contribution to stream flow or base flow by 31.67 mm. Water percolation to soil profile decreased by 1.67 mm and groundwater contribution to deep aquifers and overall aquifers (shallow and deep) decreased by 1.67 mm and 33.35 mm, respectively. Actual evapotranspiration decreased by 3.9 mm. Based on this, the average annual water yields to stream flow and sediment yield from HRU in watershed increased by 4.67 mm and 18.35 Tonnes/Ha, respectively.

The SWAT simulations of the future scenarios showed similar expected changes in water and sediment yields in the study area for the next two decades from 2021 (Table 25). Results show the average annual surface runoff or overland flow increased by 21.14 mm, water percolation to soil profile decreased by 1.27 mm, groundwater contribution to streamflow decreased by 27.95 mm, groundwater contribution to deep aquifer and overall aquifer (shallow and deep) decreased by 1.23 mm and 24.53 mm, respectively. At the same time, the average annual water yield will decrease by 13.46 mm while sediment yield in Tonnes/Ha/Year translated to increment in soil loss from 42.13 Tonnes/Ha in 2021 and projected to be 43.95 Tonnes/Ha by

2041. Furthermore, the model revealed the LULC changes have also impacted dry seasonal flow of Kilombero river.

The SWAT scenarios for LULC of 2001, 2021 and 2041 revealed a decline of average dry season (June to October) river discharge at Swero 1KB17 gauge station following LULC transformation (Fig. 26 and 27). The monthly averages at different land use scenarios are also presented in Table 26. The comparison of the data as illustrated in Fig. 26 and 27, showed that already dry season river discharge for the LULC scenarios, was already lower than recommended environmental flow (e-flow) as recommended by CDM Smith (2016). This showed that the hydro-climatic parameters that drive catchment hydrology, cannot support ecosystem integrity given the growth of sectors of economy (led by farming).

Other scholars in Tanzania and elsewhere around the world have also studied and indicated similar relationships between changes in LULC and its manifestations to increased sediment yield and surface runoff (Allan, 2004; Chilagane *et al.*, 2021; Kiersch, 2002). These changes in runoff generation agreed with the general knowledge that reducing forest/vegetation cover, decreases the opportunity of water infiltration which in turn leads to an increase in water yield due to increased surface runoff. This phenomenon brings adverse environmental issues in the catchment including soil erosion and siltation of water bodies as also observed by Kashaigili (2008) and Näschen *et al.* (2019).

Furthermore, the decrease in percolated water and hence recharge of aquifers was considered to be the aftermath of vegetation cover removal which in turn decreases the opportunity of infiltration to the extent that surface flow exceeds the gain in base flow which results in diminished dry seasonal flow as highlighted by Chilagane *et al.* (2021) and Kashaigili (2008). As pointed out in this assessment, HEP prospects by the government through a mega dam downstream will inevitably suffer the impacts of these generated sediments upstream. Furthermore, the changed flow regime, particularly dry season flows, will have negative impacts on biotic components of ecosystem found within and outside the catchment. This will include smallholder farmers livelihood dependent on the Kilombero river and its tributaries and the wildlife ecosystem in the Kibasila wetland and downstream in Nyerere National Park which will in turn impact the tourism industry.

Table 24: Historical annual hydrological summary for the watershed for 1991 to 2021

LULC Scenarios	SURQ	LATQ	GW_SHWQ	GW_DPQ	AQ_DEEP	AQ_T	WTRYLD	PERC	ET	SDYLD
1991	272.98	55.77	370.62	21	20.91	418.11	720.36	417.16	626.4	23.774
2001	274.17	55.8	369.52	20.95	20.85	416.96	720.4	416.01	626.2	24.067
2011	304.53	55.4	344.77	19.64	19.55	390.9	724.32	390.07	622.9	31.159
2021	311.64	55.11	338.95	19.33	19.24	384.76	725.03	383.94	622.5	42.125
Change	38.66	-0.66	-31.67	-1.67	-1.67	-33.35	4.67	-33.22	-3.9	18.351
(%)	14.16	-1.18	-8.55	-7.95	-7.99	-7.98	0.65	-7.96	-0.62	77.19

SURQ: Surface runoff contribution from stream flow from HRU (mm)

LATQ: Lateral flow contribution to streamflow in watershed for the day, month, or year (mm)

GW_SHWQ: Ground water contribution to stream in watershed on day, month, year (mm)

GW_DPQ: Amount of water moving from shallow aquifer to plants/soil profile in watershed during simulation (mm)

AQ_DEEP: Groundwater contribution to deep aquifer (mm)

AQ_T: Total amount of water entering both aquifers in watershed during simulation (mm)

WTRYLD: Water yield to streamflow from HRUs in watershed for simulation (mm)

PERC: Water percolation past bottom of soil profile (mm)

ET: Actual evapotranspiration in watershed (mm)

SDYLD: Sediment yield from HRUs in watershed for the simulation (Tonnes/Ha)

Table 25: Future annual hydrological summary for the watershed

LULC Scenarios	SURQ	LATQ	GW_SHWQ	GW_DPQ	AQ_DEEP	AQ_T	WTRYLD	PERC	SDYLD
2001	274.17	55.8	369.52	20.95	20.85	416.96	720.4	416.01	24.067
2021	311.64	55.11	338.95	19.33	19.24	384.76	725.03	383.94	42.125
2041	332.78	49.64	311	18.06	18.01	360.23	711.57	360.55	43.951
Change (1991 - 2021)	37.47	-0.69	-30.57	-1.62	-1.61	-32.2	4.63	-32.07	18.35
Change (%)	13.67	-1.24	-8.27	-7.73	-7.72	-7.72	0.64	-7.71	75.03
Change (2021 - 2041)	21.14	-5.47	-27.95	-1.27	-1.23	-24.53	-13.46	-23.39	1.826
Change (%)	6.78	-9.93	-8.25	-6.57	-6.39	-6.38	-1.86	-6.09	4.33

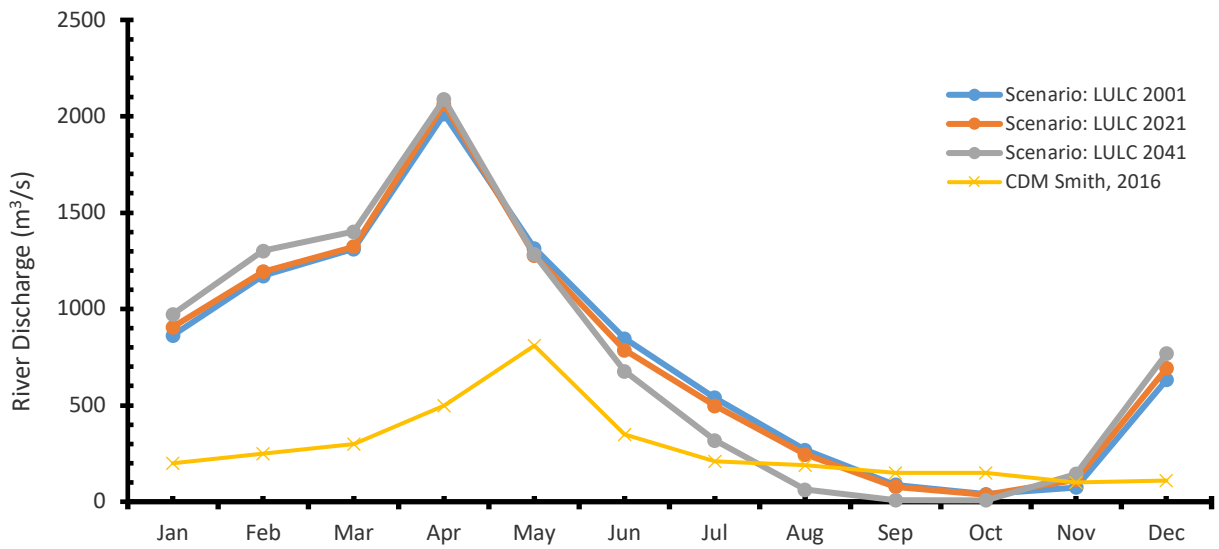


Figure 26: Seasonal average discharge in Kilombero catchment at Swero 1KB17 gauging station showing near zero dry season flow for scenario 2041 LULC: Dry seasons flow I lower than recommended e-flow

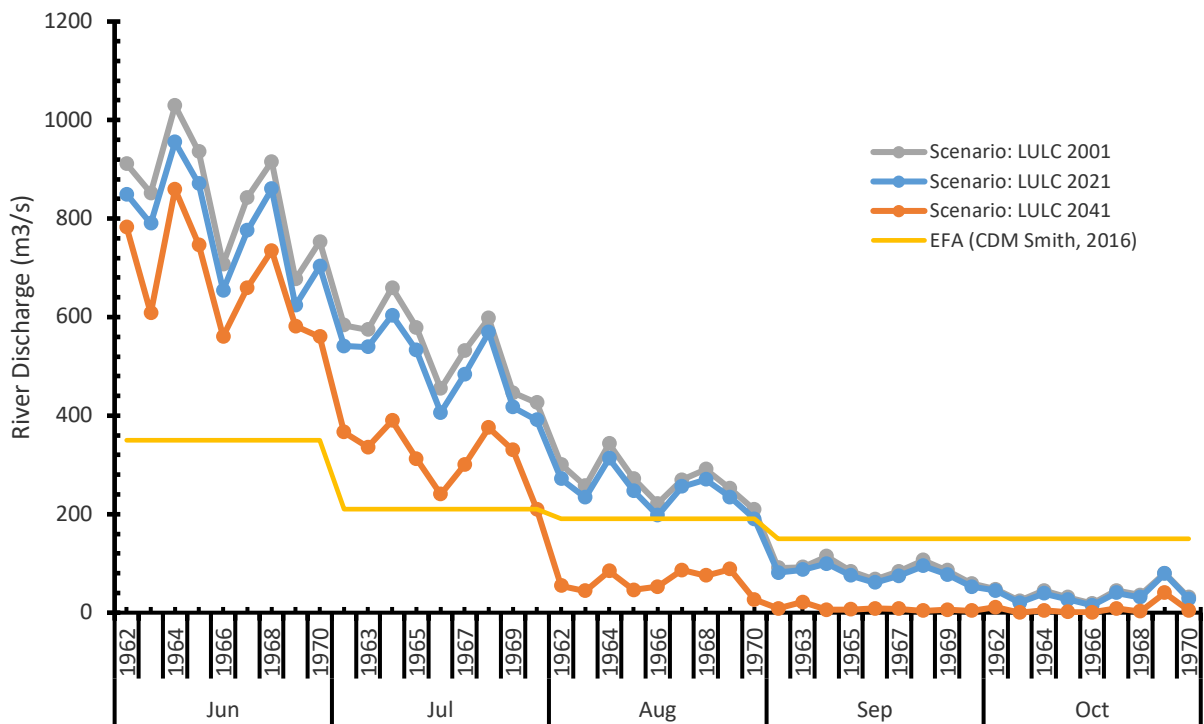


Figure 27: Show a consistent decrease in long-term dry season flow, especially the 2041 LULC during the peak of dry season i.e., June - October

Table 26: Seasonal River discharge at different LULC scenarios for 1KB17

Months	Average Discharge (m ³ /s)		
	Scenario: LULC 2001	Scenario: LULC 2021	Scenario: LULC 2041
Jan	862.44	906.22	972.88
Feb	1172.64	1194.24	1302.12
Mar	1311.34	1324.09	1402.13
Apr	2011.22	2063.11	2088.22
May	1314.17	1278.03	1283.96
Jun	847.03	786.89	677.04
Jul	539.34	498.22	317.89
Aug	268.48	246.10	62.06
Sep	87.14	78.06	8.03
Oct	39.61	35.94	8.08
Nov	74.52	113.96	144.39
Dec	633.06	692.59	769.07
Total	9161.00	9217.46	9035.87
Average	763.42	768.12	752.99

4.3.4 Contribution of Individual LULC to Surface Runoff and Sediment Yield

The proportional contribution of individual LULC to surface runoff and sediment yield is illustrated in Fig. 28 and summarized in Table 27. According to these assessment results, it was demonstrated that, cultivated land and grassland were the main contributors to both surface runoff and sediment yields with the former being the highest in both cases i.e., sediment yield of 66.37 Tonnes/Ha and water yield of 492.64 mm. These two were followed chronologically by wetland, built-up areas, woodland, and forest in terms of their contribution to generation of surface runoff. However, Bushland which was the least contributor of water runoff in this second batch, had the highest contribution of sediment yield than all of them in the batch. The change in the landmass occupied by water had negligible contributions in both sediment yield and surface runoff.

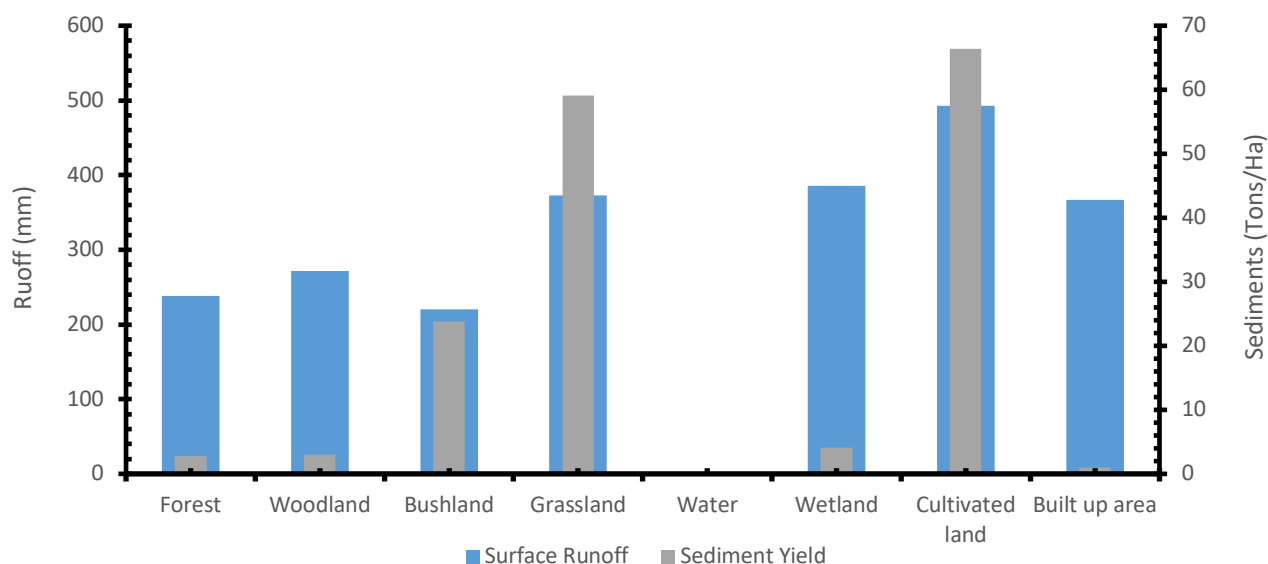


Figure 28: Contribution of individual LULC on surface runoff and sediment yield showing farms and grassland are most consequential

Table 27: Contribution of individual LULC on surface runoff and sediment yield showing farms and grassland are most consequential

Individual LULC	Surface Runoff (mm)	Sediment yield (Tonnes/Ha)
Forest	238.14	2.82
Woodland	271.39	2.98
Bushland	220.3	23.82
Grassland	372.39	59.13
Water	0	0
Wetland	385.35	4.1
Cultivated land	492.64	66.37
Built up area	366.75	1.01

4.3.5 Water Balance

The model output shows average annual water balance components (WBCs) in mm such as precipitation, evapotranspiration, surface runoff, lateral flow, percolation, return flow etc., as illustrated in Fig. 29. The water balance within SWAT involves considering precipitation as inflow to the watershed unit, while accounting for evapotranspiration and deep percolation as losses, and surface runoff, return flow, and lateral flow as outflows. According to the model results, the catchment typically received an average of 1339 mm of annual precipitation. This precipitation was then distributed among various components including evapotranspiration, surface runoff, lateral flow, shallow aquifer storage, and deep aquifer recharge.

The analysis showed that 482 mm/yr of rainfall was lost from the catchment through evapotranspiration, representing the largest component of the water balance which accounted for 36% of the rainfall received. Nearby areas of Mtera are known for higher evaporation rates

reaching as high as 160 – 200 mm/month (Yawsona *et al.*, 2003). Furthermore, it was noted that 408 mm/yr representing 30% of precipitation flows out from the catchment as surface runoff, and 3% as lateral flows. The remaining portion, about 395 mm/yr representing 29% of received precipitation percolated to shallow aquifers whereby only 19.79 mm/yr accounting for 5% of it recharged to deep aquifers while the remaining outflows the catchment as return flows.

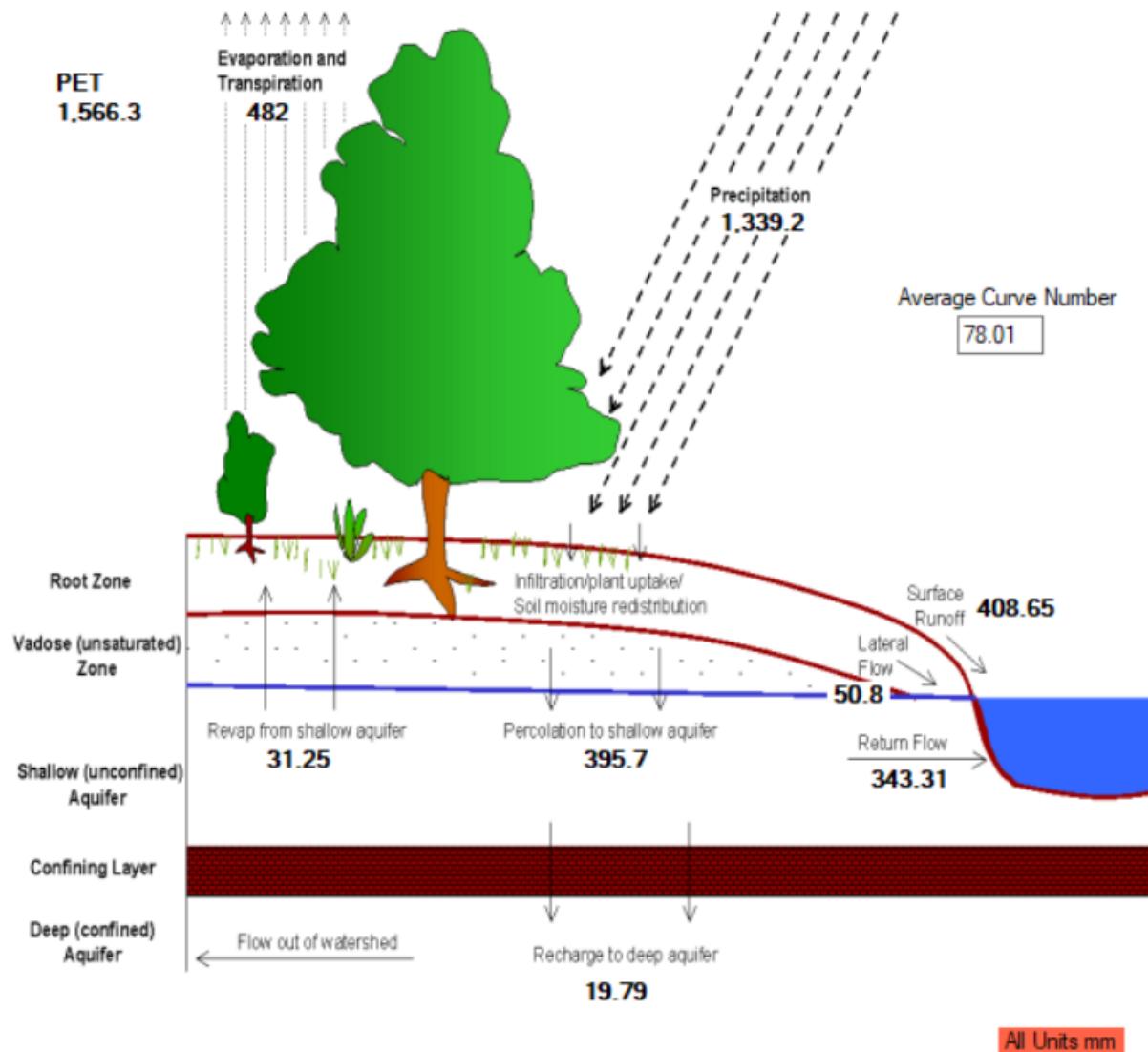


Figure 29: Modeled Water Balance for Kilombero River Catchment showing all the important components of a hydrologic system

4.4 Water Productivity

Water productivity (WP) which is a measure of value defined as the physical quantity or economic value of product derived from the use of a given quantity of water (Molden *et al.*, 2003) is one of the important criteria to consider in confronting water scarcity at present and

in the future (Mdemu *et al.*, 2013). As such, water productivity for key sectors of economy in the study area has been studied and results presented below.

4.4.1 Water Productivity in Paddy Farming

(i) Selected Socioeconomic Characteristics

The survey has shown that farming dominated livelihood activities in the study area (at 71%) followed by Small-Scale Businesses (21%), Livestock Keeping (4%) and Handcrafts especially weaving and mechanics (4%). The split in livelihood activities in the study area agreed well with studies by other scholars who also identified agriculture to be the dominant form of livelihood. This was followed by small-scale businesses and elementary occupations but all were based directly or indirectly on exploitation of natural resources (Kangalawe & Liwenga, 2005; Mtega, 2017). The study has further noted that farming was predominantly by Paddy (82%), Sugarcane (10%) and Mixed Paddy and Maize (8%) (Fig. 30).

Other crops were deemed insignificant both in terms of water use and the size of farms (e.g., bananas and vegetables). Since paddy was significant and had different types of practices especially in the small-holder segment, the study further assessed the proportion and identified four major paddy farming practices viz. rainfed conventional transplant and flooding system - CTFS (48%); irrigated CTFS (29%); rainfed system of rice intensification - SRI (14%) and irrigated SRI (9%) (Fig. 30). The same was in line with response from Ifakara Town Council (Agriculture and Livestock Department) who indicated similar split of farming systems:

Owing to fear of the unknown and general low awareness to what SRI generated both at individual and ecosystem level, more than half of paddy farmers practice conventional flooding with only a fraction picking up on SRI. The latter form a good basis to transform others as they witness them reaping more benefits [Agriculture and Livestock Department, Ifakara Town Council].

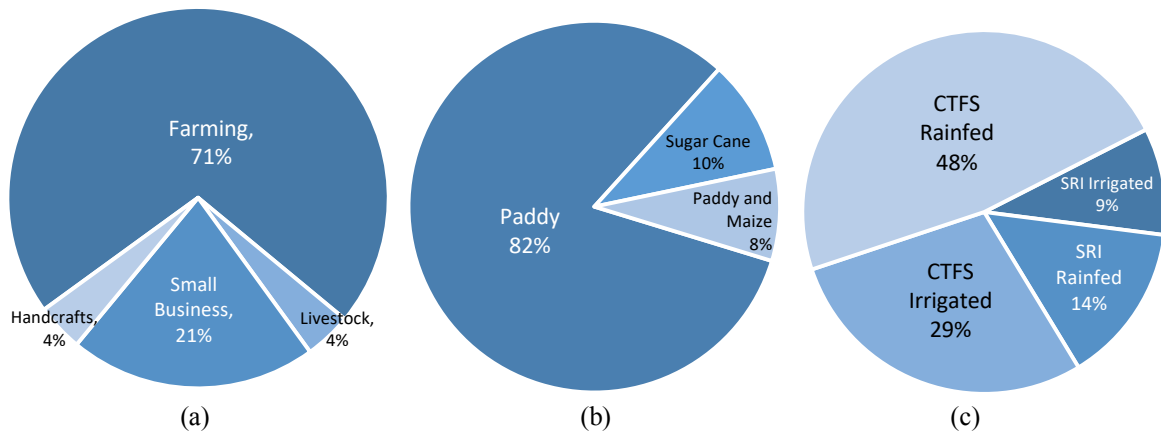


Figure 30: The proportion of: (a) livelihood activities, (b) types of crops, and (c) paddy farming practices in the study area showing paddy farming is the key livelihood activity

(ii) Farm Harvests (Paddy)

The data and results for farm harvest were adopted from Sigalla *et al.* (2022) as summarized in Table 28 and illustrated in Fig. 31. Generally, results showed that, all data are fairly symmetrical and evenly distributed but there was a huge range between lowest and highest harvest in smallholder farmers as compared to KPL investor farms (Plate 4) who had absolute and tightly packed records. While results showed SRI (Plate 5) performed better across the board, there was generally very little impact on harvest due to irrigation. For instance, increased average harvest due to irrigation was only in the tune of 0.35 Tonnes/ha (9% of average harvest in rainfed) and 0.49 Tonnes/ha (7% of average harvest in rainfed) between CTFS and SRI systems, respectively. The increment was only about 2 – 3 bags of rice that fetched around US\$ 87.06 to 113.17, which is only an average of 10% of normal income per hectare.

Comparison with Tanzania's average showed that, harvests in lowland rice farming were between 1 – 3 Tonnes/ha and 3 – 6 Tonnes/ha for rainfed and irrigated systems, respectively (Wilson & Lewis, 2015). This indicates that irrigation applications yield twice as much yield compared to rainfed systems at national average. The little impact of irrigation on harvest in KRC was attributed to the fact that most farms are fairly in good proximity to water/moisture. This is mainly the Kibasila wetland and/or the numerous perennial rivers with relatively good flows throughout the farming season. This collaborated well with a 68 years old farmer and leader of a water users association (WUA) who indicated similar harvests even in times of bad years or during dry season (where irrigation is mostly applied) which may signify the role of wetlands in water/moisture storage (Leemhuis *et al.*, 2016):

I have farmed in these areas since childhood. Even in the driest of years, we still had better harvests and no conflicts over water as compared to what we heard in Usangu during our WUA exchange visit in 2012 [68 years old farmer and leader of a water users association (WUA)].



Plate 4: A visit to a mechanized KPL farm -offseason during paddy processing and marketing



Plate 5: A visit to SRI farming plots away from wetland in Mkangawalo Village

Figure 31: Paddy harvests across the farming practices illustrating the significant results in the system of rise intensification which exceeds even mechanized KPL harvests

Table 28: Descriptive statistics for paddy harvests

N	Farming Systems	Avg. Farm size (ha)	All values are in Kg/ha					
			Mean	MIN	Q1	Q2	Q3	MAX
1	CTFS Rainfed	1.58	4058	682	2302	3240	6309	8184
2	CTFS Irrigated	0.65	4410	2450	2613	4900	5880	6533
3	SRI Rainfed	1.22	7025	4215	4740	7020	9310	9830
4	SRI Irrigated	0.73	7516	5869	6100	7259	8958	9884
5	KPL Rainfed	2003.7	3429	2230	2470	3250	4520	4920
6	KPL Irrigated	1404.3	4445	2740	3640	4380	4960	7060

* Q = Quartile

(iii) Profitability of Paddy Farming Practices

Profitability in this case was calculated in terms of gross profit margins (GPM) and return on investment (ROI). The results for GPM are presented in Table 29 and Fig. 32 whereas that of ROI are presented in Table 30 and Fig. 33. These were calculated after consideration of the income from selling paddy and all the associated costs (Table 31) across the farming systems. These amounts were obtained from questionnaire analysis where minimum, maximum and average values were established. All the presented values are in US\$ based on 1 ha of farming and are converted at an annual average rate of TZS 2297.39 for 1 US\$ as per Bank of Tanzania (BoT) rates as of 5th January 2021 (www.bot.go.tz). The calculated average values were taken as the working value as indicated in tables referenced in this section. Since KPL does not sell raw paddy, the presented numbers have been calculated retrospectively using a ratio of 1.23 Tonnes of paddy for 1 Tonne of rice as per KPL production department. Most smallholder out-growers lose most of their rice due to poor pre-processing and milling machines. On average they make 1 Tonne of rice from 1.5 Tonnes or more while our average rate is 1.23 Tonnes of paddy for 1 Tonne of rice which is one of the best in Tanzania.

Table 29: Descriptive statistics for gross profit margin for all paddy farming systems

N	Farming Systems	Avg. Farm size (ha)	Min	Q1	Median (Q2)	Q3	Max	Mean	SD
1	CTFS Rainfed	1.58	1%	2%	3%	4%	6%	3%	2%
2	CTFS Irrigated	0.65	1%	1%	2%	3%	5%	2%	1%
3	SRI Rainfed	1.22	31%	31%	40%	42%	42%	38%	5%
4	SRI Irrigated	0.73	27%	33%	41%	50%	55%	41%	10%
5	KPL Rainfed	2003.7	40%	44%	59%	70%	73%	58%	13%
6	KPL Irrigated	1404.3	34%	50%	59%	64%	74%	57%	12%

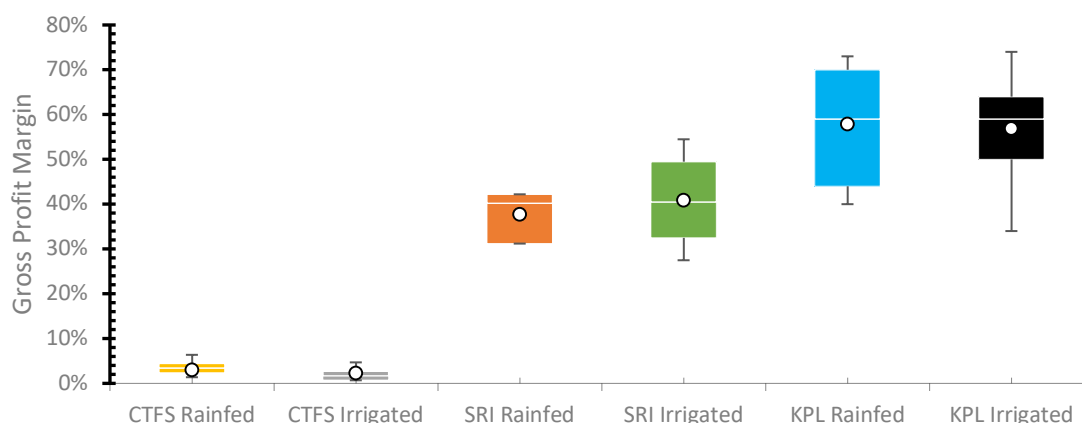


Figure 32: Comparison of gross profit margin for all the paddy farming system

Table 30: Descriptive statistics for return on investment for all paddy farming systems

N	Farming Systems	Avg. Farm size (ha)	Min	Q1	Median (Q2)	Q3	Max	Mean	SD
1	CTFS Rainfed	1.58	1%	2%	3%	5%	6%	3%	2%
2	CTFS Irrigated	0.65	1%	1%	2%	3%	5%	3%	1%
3	SRI Rainfed	1.22	45%	46%	67%	71%	73%	62%	13%
4	SRI Irrigated	0.73	38%	48%	69%	101%	121%	74%	30%
5	KPL Rainfed	2003.7	67%	84%	142%	238%	268%	155%	83%
6	KPL Irrigated	1404.3	52%	101%	142%	175%	291%	149%	74%

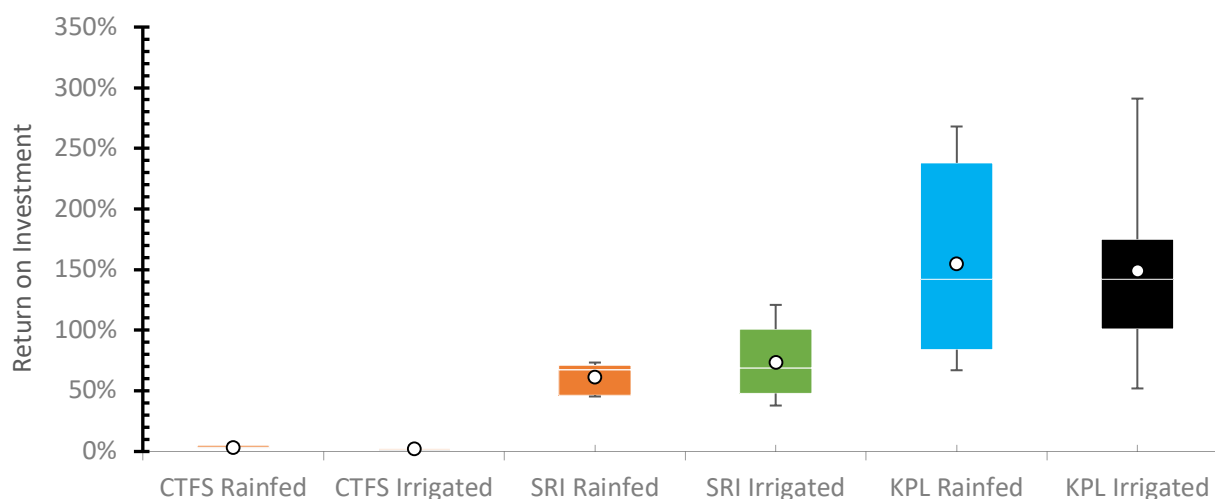


Figure 33: Comparison of return on investment across the paddy farming system

Table 31: Calculated average operational costs and annual revenue for all six farming systems

N	Farming System	Avg. Farm Size (ha)	Operational Costs (USD/ha)			Revenue (USD/ha)		
			Min	Max	Avg	Min	Max	Avg
1	Rainfed CTFS	1.58	178.22	2100.20	1043.53	180.70	2168.39	1075.16
2	Irrigated CTFS	0.65	633.01	1688.67	1133.20	646.70	1724.53	1164.06
3	Rainfed SRI	1.22	708.30	2348.62	1268.83	1032.57	3872.13	2079.48
4	Irrigated SRI	0.73	1178.0	1298.70	1248.92	1700.29	2863.65	2177.57
5	KPL Rainfed	2003.7	341.50	341.50	341.50	685.45	1511.13	1047.42
6	KPL Irrigated	1404.3	500.40	500.40	500.40	912.81	2352.62	1499.84

*These costs are based on appendix 18 showing how different inputs vary in rainfed and irrigated systems which connotes role of water usage.

With reference to Table 31, the average operational costs of small holder farmers (both CTFS and SRI) are significantly higher compared to mechanized KPL plantations. Coupled with average market prices between the smallholder (263 US\$/Tonne) and KPL (277 US\$/Tonne), the GPM and ROI were much better for mechanized farming followed by SRI (Fig. 32 and 33). The agricultural department in Mlimba District Council indicated that smaller farms per individual and poor access to markets affect accrued profits for smallholder farmers,

“Smallholder farmers in Kilombero Valley yield better than many parts of Tanzania. However, profits are slim due to poor farming practices to reduce unwanted costs, little

farms hindering resources optimization and poor road networks that affect market access”[Agriculture Department, Mlimba District Council].

Further to the results presented above, small-holder farmers (as opposed to KPL) deployed inferior technology and operated on smaller farm units which limit resources optimization. These aspects attracted higher operational costs per ha of farming compared to their mechanized farming counterparts. The aftermath of these was the recorded low profitability as demonstrated above. While improvements in accessibility infrastructure to steer markets was well captured in government plans for southern agricultural growth corridor (SAGCOT) (De Cleene, 2014), at farm level, better grounds for resources optimization were limited with smaller farms - typical practice of smallholder farmers in the study areas (Davis *et al.*, 2010; Kangalawe & Liwenga, 2005). The situation was even worse for CTFS where good agriculture practices were even more limited. This was interpreted to be one of the major reasons for persistent poor life conditions for this population segment.

Piggybacking on already existing livelihood groupings such as credit co-operative societies (SACCOS) is critical to group farmers in manageable sizes to optimize inputs (Chiteva *et al.*, 2016; Maleko *et al.*, 2013). Value addition to rice associated with branding and packaging is deemed an important strategy for lifting profitability of small holder farmers who already harvests better in terms of Tonnage notwithstanding associated operational costs. The same harvests in KRC have been shown to be better than the rest of Tanzania as indicated in (Wilson & Lewis, 2015). Needless to say, considering mechanization and other investments in KPL farms, it's impossible to imagine that small-holder led system can rise to scale of KPL as eluded in SAGCOT nucleus proposition that suggest for these out growers to learn and adopt practices in KPL (Brüntrup *et al.*, 2018).

(iv) Physical Water Productivity in Paddy Farming

Table 32 provides a summary of results for ideal water usage in terms of total decadal crop evapotranspiration in mm, the actual applied water in m³/ha (included effective rainfall and the gross irrigation water) and the real physical water productivity (PWP) in Kg/m³ (Captured as mean PWP). In addition, Table 32 also includes the ideal PWP in terms of relationship of harvest assuming that crops only consumed what is required. The latter was important to compare how far behind the real PWP was. This comparison showed that, although irrigated systems had slightly better harvests (Fig. 31), they had slightly lower PWP which explained the need for improvements in water use.

Furthermore, Fig. 34 illustrates a comparison of the real PWP for all farming systems which indicated the best performing in the study area. This showed that, with the exception to irrigated KPL system, the SRI system performs better across the board. The better results for SRI were attributed to the fact that, smallholder farms were much closer to the wetland and thereby needed even less amount of water for farming (Plate 6) and that actually SRI harvests per ha were higher than the rest. This collaborates well with observation by the agriculture department in Kilombero District Council who indicated similar experience:

It's a common experience by farmers to block flowing water during rainy season as well as dry seasons. The latter is only for those practicing SRI during dry season who form the largest segment of this practice. This is because soils are normally above field capacity during rainy season and takes little time during dry season around wetland areas [Agriculture Department, Kilombero District Council]

Table 32: Descriptive statistics for physical water productivity (PWP) in all farming systems

N	Farming Systems	ETc (mm)	Water Use (m ³ /ha)	PWP (Kg/m ³)						
				MIN	Q1	Q2	Q3	MAX	Mean	Ideal
1	CTFS Rainfed	687.7	10313	0.07	0.22	0.31	0.61	0.79	0.39	0.59
2	CTFS Irrigated	630.9	14542	0.17	0.18	0.34	0.40	0.45	0.30	0.70
3	SRI Rainfed	687.7	10313	0.41	0.46	0.68	0.90	0.95	0.68	1.02
4	SRI Irrigated	630.9	14542	0.40	0.42	0.50	0.62	0.68	0.52	1.19
5	KPL Rainfed	687.7	10313	0.22	0.24	0.32	0.44	0.48	0.33	0.50
6	KPL Irrigated	630.9	6495	0.42	0.56	0.67	0.76	1.09	0.68	0.70

Figure 34: Physical water productivity across all the farming practices

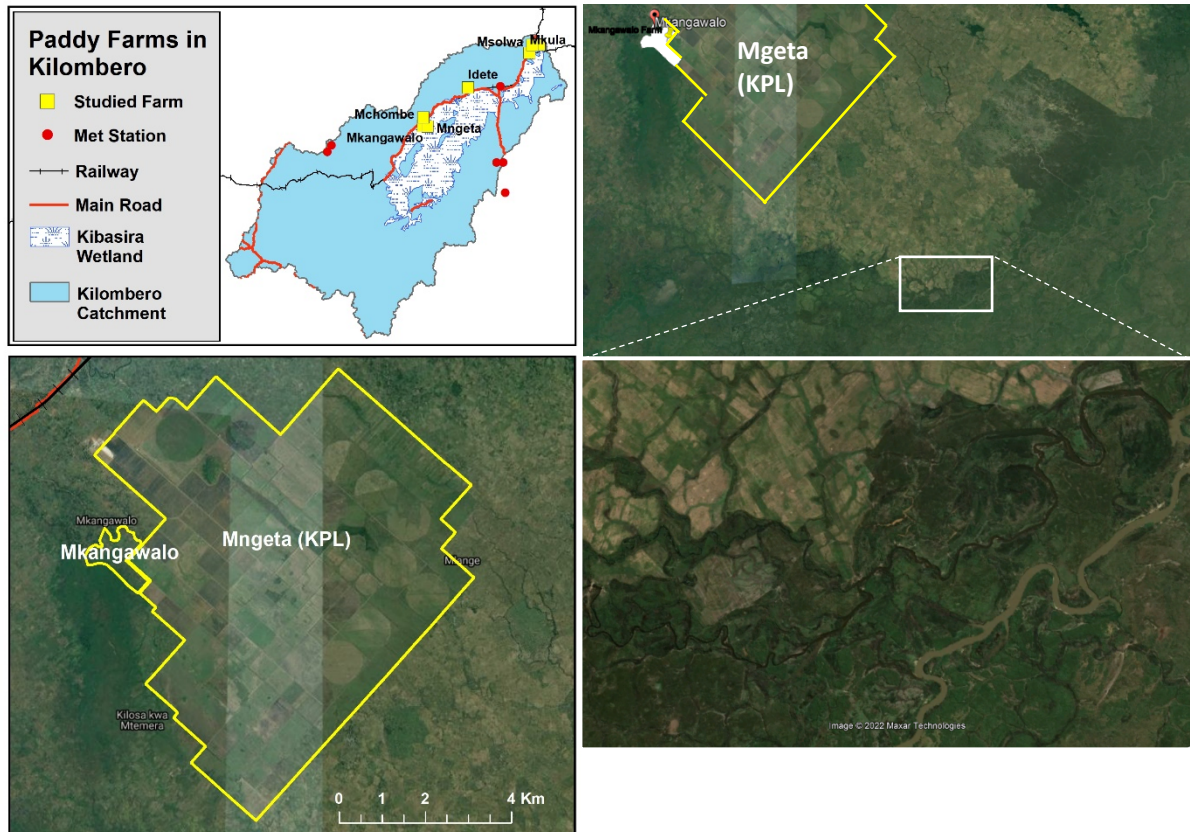


Plate 6: The spatial illustration of some of the sampled farms including illustration of small-holder farming around riverbanks/protected areas

(v) Economic Value of Water in Paddy Farming

The economic value of water (EVW) also referred by others as economic water productivity in $\text{US}\$/\text{m}^3$ was calculated using the residual imputation Approach (RIA) which helped to single out the imputed marginal economic value of water (Chiang, 2005; Mdemu *et al.*, 2013; Young, 1996). Results are summarized in Table 33 and comparison across farming systems illustrated in Fig. 35 and 36 for paddy and rice, respectively. These results show that: (a) Although KPL harvests less per ha of farming, they recorded higher EVW (esp. irrigated system) due to efficient water use and better prices by the investor as compared to smallholder farms and (b) Although naturally, value addition to rice fetches higher EVW, its irrigated component (smallholder farms) recorded less EVW compared to its corresponding rainfed system. This was linked to the loss of most of the rice due to poor milling equipment and pre-processing of paddy. The same agreed with KPL production department:

Most smallholder out growers lose most of the rice due to poor pre-preparation and milling machines. On average they make 1 Tonne of rice from 1.5 Tonnes or more while our average rate is 1.23 Tonnes of paddy for 1 Tonne of rice which is one of the best in Tanzania [KPL production department].

In addition to that, other scholars have attempted to calculate the PWP and EWP of paddy elsewhere in Tanzania as presented in Table 34.

Table 33: Summary of Economic Value of Water along with other inputs of production

N	Farming Systems		MIN	Q1	Q2	Q3	MAX	Mean	Water use m ³ /ha	Land	Labor	Capital
			All EVW are in US\$/m ³							Input values in US\$/ha		
1	CTFS Rainfed	Paddy	-0.08	-0.04	-0.02	0.06	0.11	0.003	10313	107.75	653.10	282.84
		Rice	-0.08	-0.02	0.04	0.16	0.27	0.06				
2	CTFS Irrigated	Paddy	-0.03	-0.03	0.01	0.03	0.04	0.002	14542	111.77	769.91	253.35
		Rice	-0.03	-0.02	0.03	0.05	0.062	0.02				
3	SRI Rainfed	Paddy	-0.02	-0.01	0.04	0.10	0.11	0.08	10313	161.34	838.40	285.57
		Rice	0.003	0.03	0.12	0.22	0.355	0.13				
4	SRI Irrigated	Paddy	0.03	0.03	0.06	0.09	0.11	0.06	14542	188.23	830.59	274.82
		Rice	0.05	0.05	0.08	0.12	0.14	0.09				
5	KPL Rainfed	Paddy	0.02	0.03	0.05	0.08	0.09	0.05	10313		334.48	
		Rice	0.04	0.05	0.08	0.12	0.14	0.08				
6	KPL Irrigated	Paddy	0.04	0.08	0.11	0.14	0.22	0.11	6495		495.28	
		Rice	0.09	0.14	0.19	0.22	0.35	0.19				

*Land, Labor and Capital are calculated from Appendix 18. KPL values were lumped together

0.250

Figure 35: Comparison of the EVW for paddy farming showing better values for KPL owing to better prices and markets

Figure 36: Comparison of the EVW after value addition to rice

Table 34: Comparison of water productivity values for paddy in Tanzania

N	Water Productivity	Area (region/catchment)	Research Source	Received Rainfall (mm)
1	0.30 – 0.68 Kg/m ³ 0.002 – 0.11 US\$/m ³	Study area in Kilombero catchment	Sigalla <i>et al.</i> (2022)	1200 – 1400
2	0.85 Kg/m ³ 0.23 US\$/ m ³		Musamba <i>et al.</i> (2011)	
2	0.15 – 0.51 Kg/m ³	Arusha in Kikuletwa Catchment	Kavishe <i>et al.</i> (2021)	590 – 1460
3	0.17 – 0.22 Kg/m ³ 0.02 – 0.8 US\$/m ³	Usangu in Great Ruaha catchment	Mdemu <i>et al.</i> (2013)	669
4	0.126 – 0.265 Kg/m ³ 0.01 – 0.04 US\$/m ³		Kadigi <i>et al.</i> (2004)	669
5	0.14 – 0.47 Kg/m ³	Morogoro in Wami Catchment	Kahimba <i>et al.</i> (2013)	669

Current study results fair well with other scholars

4.4.2 Water Productivity in Sugarcane Farming

Water Productivity for Sugarcane was calculated from data collected at Kilombero Sugar Company (KSC) Plantations and small-holder farmers surrounding the milling factory as presented in Appendix 13 and 14, respectively. Results show that average physical water productivity (PWP) and economic value of water (EVW) was 12.8 Kg/m³ and 0.19 USD/m³ for KSC and 8.08 Kg/m³ and 0.10 USD/m³ for small-holder farmers (Table 35 and 36). The PWP matched well with FAO database which estimated a range of 4 – 8 kg/m³ (FAO, 2023) and other scholars such as Leal *et al.* (2017) who estimated as high as 11 – 18 Kg/m³ in India. In addition, KSC secured better PWP and EVW because of good efficient water use systems and significantly low production costs per unit area respectively. This was offered by a good economy of scale at the level of their large - scale operation.

Table 35: Summary of data for PWP and EVW for Sugarcane Production at KSC

Year	Area (Ha)	Water Use (m ³)	Cane (Tonnes)	Tonnes /Ha	Profit (USD)	PWP (Kg/m ³)	EVW (USD/m ³)
2015	5672.06	29 606 397	457 019	80.57	6 817 747	15.437	0.23
2016	6047.01	61 337 569	495 356	81.92	7 477 016	8.076	0.12
2017	5984.51	29 548 743	520 897	87.04	8 186 735	17.628	0.28
2018	5522.95	36 236 260	452 519	81.93	6 831 400	12.488	0.19
2019	5304.33	28 933 123	422 388	79.63	6 247 360	14.599	0.22
2020	5695.46	37 401 014	505 059	88.68	8 030 577	13.504	0.21
2021	5452.37	53 794 524	427 493	78.40	6 250 142	7.947	0.12
Mean	5668.39	39 551 090	468 676	82.60	7 120 140	12.811	0.19

*Calculated from Appendix 13

Table 36: Summary of data for PWP and EVW for Sugarcane small-holder farms

Year	Area (Ha)	Water Use (m ³)	Cane (Tonnes)	Tonne /Ha	Profit (USD)	PWP (Kg/m ³)	EVW (USD/m ³)
2015	11 535.86	60 361 405	472 970	41	4 967 137	7.836	0.08
2016	11 702.45	61 233 085	468 098	40	4 367 901	7.645	0.07
2017	11 860.55	62 060 304	486 282	41	4 913 700	7.836	0.08
2018	15 695.43	82 126 311	627 817	40	9 130 353	7.645	0.11
2019	12 990.99	67 975 355	545 622	42	7 297 017	8.027	0.11
2020	13 287.37	69 526 177	677 656	51	10 191 465	9.747	0.15
2021	16 244.19	84 997 724	666 012	41	10 200 003	7.836	0.12
Mean	13 330.98	69 754 337	563 494	42	7 295 368	8.081	0.10

*Calculated from Appendix 14

4.4.3 Water productivity in hydropower generation

Twelve years of daily records between 2010 and 2021 has been collected from the state-owned sole energy utility company i.e., the Tanzania Electrical Supply Company (TANESCO). This documented water inlet, outlet, dam levels, turbine discharge, power generation and production costs. Table 39 and 40 provide annual average values that were used to calculate water productivity in HEP sector. Three main scenarios were considered i.e., water productivity calculated from non-consumptive that considered only turbine discharge assuming HEP did not consume any of the physical water, the consumptive scenario considered evaporation component due to dam water collection and the combined scenario which summed both the first two scenarios. Under the three scenarios, results showed a PWP of 2.06, 591.13 and 2.05 kWh/m³ and EWV of 0.19, 54.03 and 0.19 USD/m³, respectively. The significantly higher value for the consumptive use scenario was because Udzungwa escarpment where Kihansi is situated had the lowest evaporation in the catchment and is the only value considered (Näschen *et al.*, 2018; Sigalla *et al.*, 2023).

4.4.4 Decadal Consideration of PVW Across Sectors

A decade of calculated results for the economic values of water is presented in Table 37 and illustrated in Fig. 37. These were calculated from the larger compilation in Appendix 9 - 17 that was collected and collated from yearly socioeconomic profiles of KRC's riparian administrative councils of Ulanga, Ifakara, Malinyi, and Mlimba. According to these, the long-term average PVW for paddy, sugarcane and HEP were calculated to be 0.44 Kg/m³ or 0.01 US\$/m³, 6.19 Kg/m³ or 0.10 US\$/m³ and 2.05 kWh/m³ or 0.19 US\$/m³, respectively. A comparison with other previous studies showed that, the water productivity ranged in fairly the same values Table 38. This means that superior economic return after use of a unit of water was in this same order.

However, although the value of a unit of water was lowest in paddy or farming generally vs HEP, it was considered the most consequential sector when it came to food and employment security. This was signified by the fact that, across Africa, agriculture forms an important source of livelihoods in rural areas, with a total share of income ranging from 59% to 78% (Blein *et al.*, 2017; Davis *et al.*, 2010).

In Tanzania, the sector contributed around 28.9% to the national GDP and employs about 65% of total population in the country which was close to 60 Million people (NBS, 2020; Rudari *et al.*, 2019). In KRC alone, farming commanded 71% (of which Paddy is 82%) of all livelihood activities (Sigalla *et al.*, 2022). Adopting more efficient technologies such as SRI will improve water productivity for paddy. Similarly, grouping farmers in appropriate segments might improve their bargaining power and hence secure better prices and hence economic value of water (Sigalla *et al.*, 2022).

Table 37: Decadal productivity value of water for KRC riparian districts

N	Years	PWP			EVW (US\$/m ³)		
		Paddy (Kg/m ³)	Cane (Kg/m ³)	HEP (kWh/m ³)	Paddy	Cane	HEP
1	2010	0.32	5.44	2.09	0.001	0.076	0.19
2	2011	0.32	5.56	2.07	0.001	0.068	0.19
3	2012	0.31	6.41	2.11	0.002	0.038	0.19
4	2013	0.34	5.38	2.01	0.002	0.068	0.18
5	2014	0.46	6.19	2.06	0.002	0.083	0.19
6	2015	0.46	6.19	2.07	0.009	0.090	0.19
7	2016	0.46	6.86	2.07	0.010	0.170	0.19
8	2017	0.55	6.18	1.86	0.027	0.152	0.17
9	2018	0.58	6.13	2.06	0.034	0.151	0.19
10	2019	0.46	6.97	2.06	0.010	0.116	0.19
11	2020	0.56	6.87	2.06	0.027	0.114	0.19
12	2021	0.46	5.97	2.06	0.011	0.096	0.19
Average		0.44	6.18	2.05	0.01	0.10	0.19

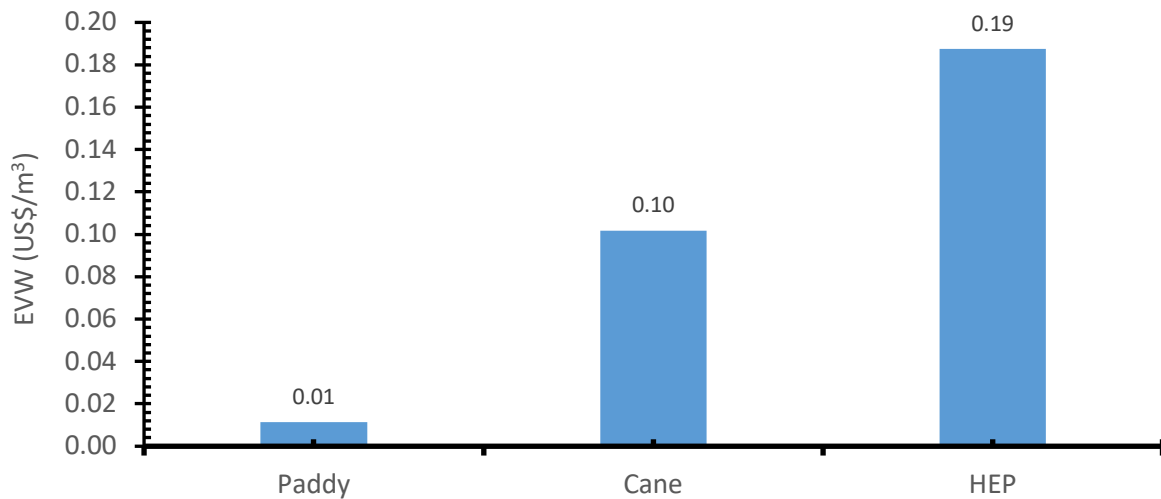


Figure 37: Decadal average EVW for main sectors of the economy showing favorable results for HEP. However, this has more impact to macro/national level economics than local livelihoods which are attached to agriculture

Table 38: Comparison of Water Productivity for the same sectors but different scholars showing similar range of WP in other areas

N	Sector	Water Productivity		Source for Others
		Current Study	Others	
			Ref.	
1	Paddy	0.44 Kg/m ³ or 0.01US\$/m ³		
2	Sugarcane	6.19 Kg/ m ³ or 0.01US\$/m ³	4 – 8 kg/m ³ ; 11 – 18 Kg/m ³	FAO, (2023) and Leal <i>et al.</i> (2017)
3	HEP	2.05 kWh/ m ³ or 0.19 US\$/m ³	0.45 – 1.68 kWh/m ³ or 0.06 – 0.21 US\$/m ³	Kadigi <i>et al.</i> (2005, 2008)

Table 39: Calculated water productivity across the years for HEP at Kihansi plant

Generation Item	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Total Generation (kWh) x 10 ⁶	867.32	774.22	592.88	795.65	861.99	836.77	793.83	815.02	772.25	956.58	806.35	770.63	803.62
Total Water Use (m ³) x 10 ⁶	412.78	373.45	279.88	394.38	416.14	403.72	383.06	435.73	373.05	462.08	389.16	372.45	391.32
PWP (kWh/m ³)	2.10	2.07	2.12	2.02	2.07	2.07	2.07	1.87	2.07	2.07	2.07	2.07	2.06
Average Tariff (USD/kWh)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Annual Turnover (USD) x 10 ⁶	89.47	79.87	61.16	82.08	88.92	86.32	81.89	84.08	79.67	98.68	83.18	79.50	82.90
Generation Costs (USD/kWh)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Annual Gen Costs (USD) x 10 ⁶	10.19	9.10	6.97	9.35	10.13	9.83	9.33	9.58	9.08	11.24	9.48	9.06	9.44
Annual Net Profit (USD) x 10 ⁶	79.28	70.77	54.19	72.73	78.79	76.49	72.56	74.50	70.59	87.44	73.71	70.44	73.46
Net - EWP (USD/m ³)	0.19	0.19	0.19	0.18	0.19	0.19	0.19	0.17	0.19	0.19	0.19	0.19	0.19
Raw - EWP (USD/m ³)	0.22	0.21	0.22	0.21	0.21	0.21	0.21	0.19	0.21	0.21	0.21	0.21	0.21
Consumptive (Evaporation) component													
Reservoir area (m ²) x 10 ⁴	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00
Evaporation (m)	5.27	5.19	5.24	5.31	5.18	5.26	5.20	5.24	5.19	5.17	5.13	5.40	5.23
Vol evaporated (m ³) x10 ⁶	1.37	1.35	1.36	1.38	1.35	1.37	1.35	1.36	1.35	1.34	1.33	1.40	1.36
PWP (kWh/m ³)	633.39	573.56	435.04	576.49	640.65	612.05	587.16	598.03	572.10	712.09	604.16	548.86	591.13
Raw - EWP (US\$/m ³)	65.34	59.17	44.88	59.47	66.09	63.14	60.57	61.69	59.02	73.46	62.33	56.62	60.98
Net - EWP (USD/m ³)	57.90	52.43	39.77	52.70	58.56	55.95	53.67	54.67	52.30	65.09	55.22	50.17	54.03
Evaporation and turbine discharge component													
Vol of water (m ³) x 10 ⁶	414.15	374.80	281.24	395.76	417.48	405.09	384.41	437.10	374.40	463.42	390.50	373.85	392.68
PWP (kWh/m ³)	2.09	2.07	2.11	2.01	2.06	2.07	2.07	1.86	2.06	2.06	2.06	2.06	2.05
Raw - EWP (US\$/m ³)	0.22	0.21	0.22	0.21	0.21	0.21	0.21	0.19	0.21	0.21	0.21	0.21	0.21
Net - EPW (US\$/m ³)	0.19	0.19	0.19	0.18	0.19	0.19	0.19	0.17	0.19	0.19	0.19	0.19	0.19

Table 40: Summarized water productivity under different scenarios at Kihansi HEP

Item Description	Scenarios		
	Non-Consumptive	Consumptive	Combined
Generation Component			
Annual Generation (kWh) x 10 ⁶		803.62	
Average Tariff (US\$/kWh)		0.10	
Average Generation Costs (US\$/kWh)		0.01	
Annual Generation Costs (US\$) x 1M		9.44	
Annual Turnover (US\$) x 10 ⁶		82.90	
Turnover Less Costs (US\$) x 10 ⁶		73.46	
Water Use Component			
Annual Turbine Discharge (MCM)	391.32		
Evaporated Volume (m ³) x 10 ⁴		136.01	
Combine Water Use (MCM)			392.68
Water Value/Productivity			
Physical Water Productivity (kWh/m ³)	2.06	591.13	2.05
Lumped Economic Value of Water (US\$/m ³)	0.21	60.98	0.21
Residual Economic Value of Water (US\$/m ³)	0.19	54.03	0.19

4.5 Hydro-Economic Tradeoffs

As pointed out above; to understand the tradeoffs across the productivity/economic values of water in the main sectors of economy under consideration, the marginal productivity of water (MPW) approach was used. In this regard, sugarcane fetched the highest value but was the most unstable/elastic. On the other hand, paddy and HEP presented almost synonymous patterns and the least of them. This was attributed to the unstable sugar markets associated with a market monopoly in the country where sugarcane producers were the same ones with permits to import the product (Kangile *et al.*, 2022).

Amongst other policy arguments, Kangile *et al.* (2022) further pointed out that abrupt trade policy changes have had a significant ($p < .05$) impact on the reduction of commodity trade by 47.7%. This also lowered the overall level of efforts to invest within the sugar supply chain. Furthermore, a previous study by Vijayakumar and Bozward (2025) on the impacts of global market for sugar, rice, wheat and cotton in developing nations showed a weak bargaining position that these nations had. He further proposed that concerted efforts of regional policymakers are necessary to reduce the extent of monopoly power in these marketing chains and to improve the degree of price transmission (Kilima, 2006; Vijayakumar & Bozward, 2025).

Further analysis of data as illustrated in Fig. 38 and summarized in Table 41, showed that MPW in paddy farming was relatively stable with very slight increasing returns over the years with a maximum achieved in 2017. However, this started ditching consistently right after 2018 to an extent that the sector starts to experience diminishing returns from around 2019. This is because after this year, the change in profit was negative between the two consecutive years (a loss), or water used was reduced (negative) compared to the presiding year. For HEP, though slight, but each year the sector recorded increasing returns which could be explained by the fact that HEP is mostly stable in terms of revenue/profit and use of water. The stable use of water was attributed to the suitable positioning of the Kihans dam, which is upstream of any water use and actually within the protected Udzungwa mountain ranges where evaporation losses were also minimal (Sigalla *et al.*, 2023). The measure of accuracy of these MPW calculations for paddy, sugarcane and HEP were $p < 0.01$, $p < 0.06$ and $p < 0.1$, respectively (Table 42).

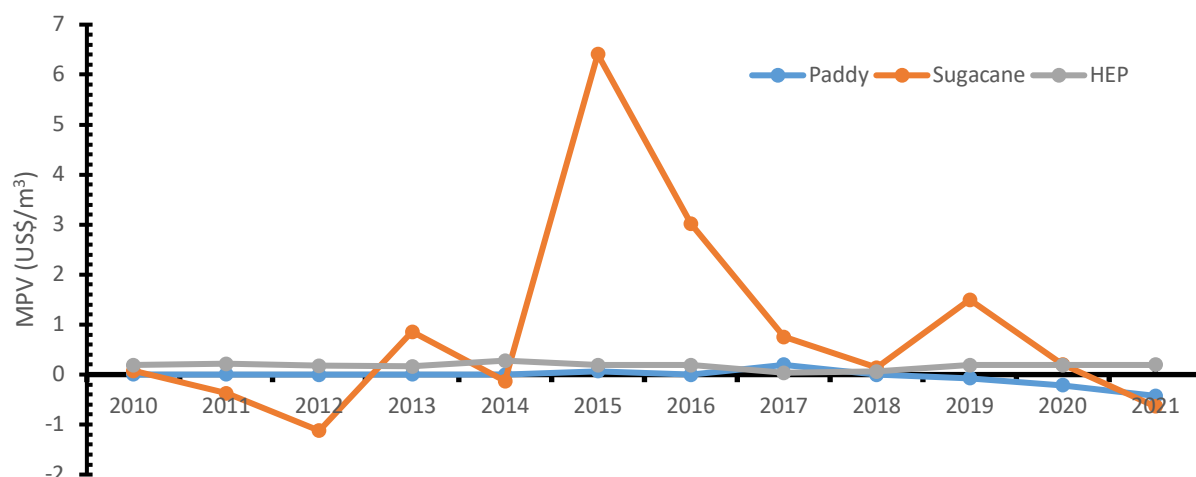


Figure 38: Marginal productivity of water for different sectors of economy indicating sugarcane farming to fetch higher value for an additional unit of water. However, results show highly varying elasticity

Table 41: Accuracy assessment for the calculation of marginal productivity water

Variables	Paddy	Sugarcane	HEP
Profit	1.06e-09*** (0)	6.59e-09*** (-6.21e-11)	2.29e-09*** (0)
Water use	-0** (0)	-7.06e-10*** (7.73e-11)	-4.39e-10*** (0)
Constant	0.00643** (0.00265)	0.107*** (0.0115)	(0) (0.000091)
Observation	12	12	12
R-squared	0.989	0.999	0.997

Standard errors in parentheses
 *** $p < 0.01$, ** $p < 0.05$, $p < 0.1$

Table 42: Summary of MPV of water for the three economic sectors

Years	Change Profit (US\$)			Change Water Use (m ³)			MPV of Water (US\$/m ³)		
	Paddy	Cane	HEP	Paddy	Cane	HEP	Paddy	Cane	HEP
2010	1 083 424	11 004 882	79 279 676	737 678 261	145 425 692	414 148 494.28	0.001469	0.075674	0.191428
2011	-79 825	-914 272	-8 510 127	-25 873 913	2 422 462	-39 349 832	0.003085	-0.37741	0.216268
2012	160 966	-4 353 658	-16 575 334	-35 278 261	3 878 308	-93 557 735	-0.00456	-1.12257	0.177167
2013	520 041	4 965 779	18 534 501	192 715 217	5 790 923	114 516 621	0.002698	0.857511	0.16185
2014	-179 067	1 414 413	6 064 305	91 060 870	-10 76 538	21 724 880	-0.00197	-0.13136	0.279141
2015	8 325 087	1 104 499	-2 305 421	118 728 261	172 409	-12 393 593	0.070119	6.406265	0.186017
2016	275 364	12 400 051	-3 924 756	-103 305 217	4 112 705	-20 677 537	-0.00267	3.01506	0.189808
2017	18 905 499	-3 253 636	1 936 703	97 779 130	-4 328 860	52 684 080	0.193349	0.751615	0.036761
2018	604 026	1 796 922	-3 910 006	-204 018 261	13 319 774	-62 699 610	-0.00296	0.134906	0.062361
2019	-18 607 523	-6 010 290	16 849 365	258 976 957	-4 025 071	89 029 219	-0.07185	1.493213	0.189257
2020	17 494 607	-710 214	-13 732 330	-80 703 478	-3 484 248	-72 928 349	-0.21678	0.203836	0.188299
2021	-16 939 020	-2 479 324	-3 264 679	39 746 957	3 906 877	-16 643 262	-0.42617	-0.63461	0.196156

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research was intended to assess the hydro-economic limits of Kilombero river catchment (KRC) and propose efficient tradeoff across the competing sectors of economy. This entailed a combination of assessments on hydrological, climatic trends and limits vs the ever-growing sectors of the economy and the varying impacts/benefits of applying a unit of water to the respective sectors. In this regard, the key hydroclimatic parameters under consideration for catchment carrying capacity consideration included precipitation, temperature, evapotranspiration, river discharge and LULC trends. These helped in developing an understanding of their interaction, hence the resultant water quantity and quality (sediment generation). On the other hand, sectors of economy considered in this research focused on hydroelectric production and farming of mainly paddy and sugarcane which occupied 92% of livelihood activities in the KRC that is characteristic of a typical rural setting. The KRC was chosen as a case study because it presented a unique water-energy-food (WEF) nexus which is one of the main puzzles facing water allocation decisions in the world. In addition, this was a critical catchment as it provided more than 62% of the total discharge of the Rufiji River to the Indian Ocean and the largest contributor of flow to the government's flagship HEP project at Nyerere Dam. Furthermore, the impairment of its existing good state is inevitable given all the SAGCOT expansion plans that will be catalyzed by the ongoing construction of major highway between Mikumi and Namtumbo expected to spur an unprecedented expansion of economic activities.

In this study, the statistical trend analysis has demonstrated that, except for the declining trend of potential evapotranspiration (PET), all other variables were increasing in the historical consideration (1981 – 2020). However, owing to impacts of climate change, the future (2021-2051) rainfall projections showed a declining trend while temperature both minimum and maximum and evapotranspiration showed an increasing trend. Furthermore, an additional attempt was carried out to understand the relationship between LULC changes and that of hydroclimatic parameters and their manifestation to the water quality and quantity in the catchment. Assessment results for the period under consideration i.e., 1991 to 2021 and as projected to 2041 showed that there was a general increase in surface runoff and sediment yield in the catchment. These LULC changes have negatively impacted dry season flow of the river

with a consistent declination from the different LULC scenarios of 2001, 2021 and 2041. This decline was to the level that was lower than the recommended dry season flow which signified the limited catchment carrying capacity. These results were attributable to the decrease in vegetation cover and expansion of land tillage activities that caused an overall increase in runoff and sediment yield while groundwater recharge dropped for both shallow and deep aquifers.

The LULC results gave an attestation of this situation as they indicated that, between 1991 and 2021, there was a major percentage loss in the size of land experienced by water, forest, woodland and wetland which decreased significantly and threatens a sustainable future of this catchment. On the other hand, percentage increases during the same period were experienced in cultivated land, built up areas and grasslands which increased considerably to the detriment of the ecosystem services offered by the catchment. However, an independent analysis of the observed river flow shows that the expansions of these thirsty sectors have not reversed the increasing water discharged out of the Kilombero river catchment as recorded at Swero (1KB17) gauge station. This was suggestive of the sedimentation accumulation at the station as indicated in SWAT results on increasing of the same or the fact that most of the hydroclimatic parameters were on increase as pointed out above.

The current study has further demonstrated the productivity values of water (PVW) (both physical and economic) according to local practices within the considered economic sectors and averaged decadal values for the entire catchment. This has shown that, at catchment level, the average PVW is highest in HEP sector followed by sugarcane and lastly paddy farming. Agricultural sectors, had PVW ranging across farming practices. For instance, paddy with four different farming practices recorded the highest values in the system of rice intensification (SRI) which also had highest PWP even surpassing mechanized farming by Kilombero plantation (KPL). The observed superiority of smallholder paddy farming, particularly under the System of Rice Intensification (SRI), over mechanized systems under Kilombero Plantation Limited (KPL) is attributable to the fact that smallholder farmers engage in fertile and wet areas (some are protected areas as demonstrated).

In addition, limited water uses under SRI coupled with agronomic practices, and adaptability to local conditions adds to the performance of SRI. This is consistent with existing literature that highlights SRI's potential to enhance yields while using significantly less water through methods such as alternate wetting and drying, wider spacing, and careful seed selection (Anas

et al., 2011; Uphoff *et al.*, 2011). Smallholder farmers, being more flexible and responsive to local ecological cues, can adopt these water-saving techniques more effectively than large-scale mechanized systems, which often rely on uniform and rigid operational routines.

Furthermore, mechanized systems may focus on maximizing land or labor productivity rather than water efficiency, potentially leading to relatively higher water losses or suboptimal water use in regions where irrigation infrastructure and management are limited. Thus, the higher PVW from smallholder SRI-based paddy farming underscores the importance of context-appropriate, knowledge-intensive practices over capital-intensive ones in water-scarce tropical catchments like Kilombero. On the other hand, sugarcane farming indicated that conventional small holder farmers recorded the lowest PVW across the board. These values compare well with results from other scholars who studied elsewhere in Tanzania or in comparable tropical climate.

After assessing the PVW, it was important to measure where this resource generated maximum revenue in terms of increasing returns for a change in water use. This was necessary since it is plausible for water users to seek maximization of water use for their respective sectors without comparing the economic impact brought about by the said water use. As such, the marginal productivity of water (MPW) was calculated and studied over a period between 2010 and 2021 based on data availability. This indicated that paddy and HEP had the lowest and unfluctuating MPW while sugarcane recorded the highest but elastic increasing returns for additional units of water. Given the impact of agriculture for rural livelihood and particularly paddy in Kilombero where it commands 82% of livelihood, we concluded that it will be detrimental to favor sugarcane production or HEP on economic terms (MPW) alone. This is because paddy provided both food and employment security, the like of which no other sector did. This does not withstand the impact of these other sectors on a national stage where paddy also plays a pivotal role.

5.2 Recommendations

Based on the assessment results and conclusions drawn above, the study realized several policy and research gaps that could better the propositions. This will not only help to further the knowledge but also sustain the ecosystem benefits that KRC is poised to provide in the larger Rufiji River Basin or the nation at large. The following are the proposed recommendations that the study have put forward for research, operational/management and policy actors:

5.2.1 Research recommendations

- (i) Update the e-flow values for different strategic stretches based on hydrology, ecology, geomorphology, climate and other factors such as stretches before the escarpments, flood plain, wetland stretch and downstream of wetland. Also study the implication of the updated e-flow values to the downstream water users (e.g., the flagship Nyerere HEP project, the farming/fishing in the Rufiji Delta and the mangrove/coastal ecosystems).
- (ii) Carryout research into how and what an optimum grouping of farmers should be e.g., size of land, market opportunities and/or ecoregions that will improve their economies of scale and exchange of experiences.
- (iii) SRI has proven to be a more profitable smallholder farming practice of paddy crops, and it fetched the highest PVW. However, there is conspicuous slow adoption or general reluctance whose key drivers need to be researched.
- (iv) Research on responsiveness of the recommendations of the statutory 2012 IWRMD planning exercise vs improvements in water availability (quantity and quality) in time and space.
- (v) Build on findings of this study by considering specific studies for impacts of water across the agriculture value chain beyond farming alone i.e., value addition, logistics, marketing, food security etc. The same for ecosystem/environmental services and incorporate investment costs with depreciation/appreciation aspects of assets.

5.2.2 Operational/management recommendations

- (i) Update and operationalize a strategic river gauge station including the Kilombero at Swero (1KB17), Kilombero at Felly 1KB2A and hydroclimatic monitoring of the larger Kibasila wetland and major tributaries. This will help to update the e-flow requirements of the different catchment sections that will inform the first building block of water allocation.
- (ii) The riparian administrative councils should organize farmers into optimal groupings to minimize inefficient use of resources resulting from poor economies of scale. The

existing experience in rural cooperative societies, along with both formal and informal credit and support systems such as SACCOS provide a strong foundation to build upon.

- (iii) Rollout LULC and water allocation plans in line with infrastructure development like the planned highway construction and SAGCOT expansions in Kilombero cluster (corresponding to the hydrologic catchment). This will ensure harmony among the catchment dwellers, the environment and economic growth.
- (iv) Promote a blend of SRI practices on rainfed paddy farming to improve food security, local incomes and water serving for downstream users.

5.2.3 Policy recommendations

- (i) Rufiji Basin Water Board (RBWB) and the Ministry of Water (MoW) need to enhance collaboration with the Ministry responsible for agriculture and Land Use Commission to improve enforcement of water and land use plans that promote conservation agriculture and other sustainable development practices that improve the catchment hydrologic carrying capacity.
- (ii) RBWB, MoW, TMA and research institutions to improve collaborations that increase accessibility of data and thereby research findings that inform sound decision making.
- (iii) The Ministry that is responsible for cooperatives to provide and strengthen policy, legal and institutional environments to catalyze and sustain farmers groupings that help with sharing of knowledge, minimizing unit cost of production and bargaining power for better markets/prices.
- (iv) The Ministry of agriculture in collaboration with the Ministry of Water and other relevant agencies needs to draft financial and legal incentives to compel adoption of efficient farming practices such as SRI. These should be embedded in cultural structures of decision making for robust and sustainable adoption.
- (v) Introduction and emphasis on environmental conservation from elementary schools' curriculum for a more guaranteed behavior change.

5.2.4 Next Steps

The researcher in collaborations with different authorities and actors intends to:

- (i) Developing thematic policy briefs and engages relevant ministries, research institutions, and local governments to implement the recommended management actions.
- (ii) Through the National Multi Stakeholders Platform on Water Resources Management, present and encourage inter-ministerial and cross-sectoral task forces to develop and execute the proposed policy frameworks.
- (iii) Develop project proposals to secure funding through government budgets and international donors to support both research and operational upgrades.
- (iv) Monitor progress of recommendation uptake using performance metrics and adjust strategies accordingly.

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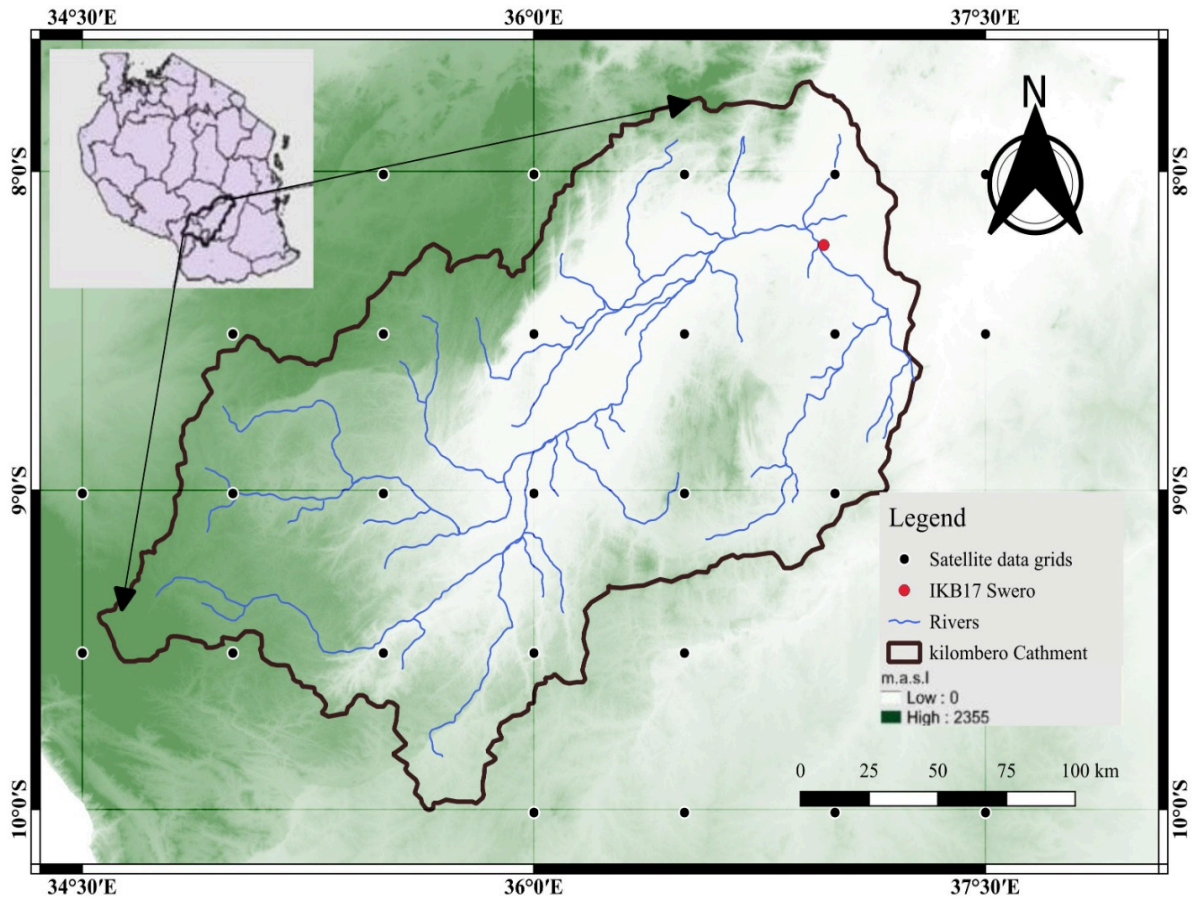
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APPENDICES

Appendix 1: Spatial distribution of data stations illustrating satellite and daily observed hydroclimatic stations



Appendix 2: Data set used in this study indicating the type of data procured, the range, resolution and source of data

N	Station Name	Range	Data Type	Resolution	Source
1	Kilombero at Swero	1957 - 1981	Observed Discharge	Daily	RBWB
2	Ifakara MET	2017 - 2019	Observed precipitation & Temperature	Daily	
3	Mngeta MET		Daily		
4	Echidna	1951 - 2009	Precipitation	Daily	TMA
5	Kwiro	1933 - 2009			
6	Mahenge Hosp	1950 - 2008			
7	Mahenge RF	1993 - 2019			
8	Matugutu	1961 – 2015			
9	Ruaha Mission	1950 - 2002	Temperature	Daily	
10	Mahenge	1993 - 2019			
11	29 Satellite station grids	1981 - 2020	Precipitation	Daily	CHIRP
			Temperature		ORH
			Evaporation		Calculated from Temp.
12	DEM	N/A	Elevation	90 m spatial	SRTM
13	KNMI Regional Atmospheric Climate Model, version 2.2 (RACMO2.2T)	2021 – 2050	Precipitation	Monthly	Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands
			Temperature		
			Evaporation		

Appendix 3: Summary of satellite imagery data for all time epochs

Year	Spacecraft ID	Sensor ID	Path/Row	Acquisition Date	Cloud Cover (%)
1991	Landsat 5	TM (SAM)	167/65	05/06/1991	4
		TM (SAM)	167/66	24/08/1991	10
		TM (SAM)	168/65	15/08/1991	2
		TM (SAM)	168/66	15/08/1991	8
		TM (SAM)	168/67	15/08/1991	4
2001	Landsat 7	ETM (SAM)	167/65	07/07/2000	2
		ETM (SAM)	167/66	07/07/2000	1
		ETM (SAM)	168/65	06/09/2002	1
		ETM (SAM)	168/66	18/06/2002	7
		ETM (SAM)	168/67	18/06/2002	10
2011	Landsat 5/7	ETM (BUMPER)	167/65	08/07/2012	6
		ETM (BMPER)	167/66	23/08/2011	10
		TM (SAM)	168/65	21/07/2011	3
		TM (SAM)	168/66	05/07/2011	3
		TM (SAM)	168/67	05/07/2011	5
2021	Landsat 8	OLI_TIRS	167/65	26/08/2021	13
		OLI_TIRS	167/66	09/07/2021	1
		OLI_TIRS	168/65	05/11/2021	2
		OLI_TIRS	168/66	24/11/2021	2
		OLI_TIRS	168/67	24/11/2021	1

Appendix 4: Summary of type of data and its source

N	Key data	HEP	Sugarcane		Paddy	
			KSCL	Smallholder	KPL	Smallholder
1	Water consumption	Daily observed at Kihans	Daily observed at intake	Estimated volume from permit	Daily observed at intake	Estimated volume from permit
2	Product output	Daily records	Annual records at farm	Farm, aggregation points and district records	Annual records	Farm, aggregation points and district records
3	Output value	Daily records based on kW value	Annual records at farm	Calculated from average price from farmer response, aggregation points and district records	Annual records at farm	Calculated from average price from farmer response, aggregation points and district records
4	Other inputs value	*None	*Annual records	Triangulated average	*Annual records	Triangulated average
5	Expenditure data	*Calculated from average cost of a kW	*Annual records	Triangulated average	*Annual records	Triangulated average

*Doesn't include inputs such as labor (salaries) or expenses like taxes which were confidential information not shared.

Appendix 5: Description of LULC classification scheme elaborating the different classes

Land use/cover	Description
Forest	Area of land covered with at least 10% tree crown cover, naturally grown or planted and or 50% or more shrub and tree regeneration cover
Woodland	Area of land covered with low density trees with height between forming closed to open habitat with plenty of sunlight and limited shade
Bushland	Area dominated with bushes and shrubs with occasional short emergent trees
Grassland	Land area dominated by grasses
Water body	Area within body of land, filled with water, localized in a basin, which rivers flow into or out of them
Wetland	Land area that is saturated with water either permanent or seasonally including valley bottoms
Cultivated land	Area subjected to agricultural production farms with crops and harvested crop land
Built up area	Manmade infrastructure (roads and buildings) and settlement (town and villages)

Appendix 6: Conditional transition probabilities of each LULC transforming to another

Assigned LULC	Probability of changing to							
	Forest	Woodland	Bushland	Grassland	Water	Wetland	Cultivation	Built area
Forest	0.562	0.2071	0.2001	0.0033	0.0004	0.0004	0.0264	0.0004
Woodland	0.1174	0.351	0.4532	0.0129	0.0002	0.0022	0.0624	0.0006
Bushland	0.0855	0.1676	0.5174	0.0346	0.0003	0.0049	0.1873	0.0023
Grassland	0.0087	0.0087	0.3084	0.3346	0.0003	0.0004	0.3356	0.0033
Water	0.0413	0.1201	0.0886	0.0035	0.669	0.026	0.0515	0.0001
Wetland	0.0039	0.0303	0.0595	0.0051	0.0028	0.6302	0.2682	0
Cultivation	0.0592	0.0192	0.1374	0.0176	0.0002	0.0011	0.754	0.0114
Built area	0.0157	0.029	0.0844	0.0416	0.0001	0	0.1858	0.6434

Appendix 7: Demographic data on sampled villages and details of sample size

N	Village Name	Ward	Selected Village Demography				Sampled population		
			M	F	Total	HH	M	F	Total
1	Mkangawalo	Mngeta	1655	1796	3451	633	63	28	91
2	ITonnegowa	Mngeta	1219	1475	2694	321	35	11	46
3	Kidete	Mngeta	820	744	1564	253	26	10	36
4	Njage	Mchombe	624	723	1347	298	31	11	42
5	Mkula	Mkula	683	785	1468	230	19	16	35
Total			5001	5523	10 524	1735	174	76	250

Appendix 8: Key informant respondents and type of data collected

S/N	KII Respondent	Respondents	Department/Section	Data collected
1	District Council of Ifakara, Mlimba, Malinyi and Ulanga Rufiji Basin Water	4	Agric & Irrigation	Harvests, Prices, types of farming practices
2	Board (Ifakara Sub Office)	1	Head of Office	Water uses, water permits
3	Kilombero Agricultural Training and Research Institute	1	Crop Science	Soil, Moisture levels and farming practices
4	KPL plantations Ltd	2	Production and Irrigation	Water use, inputs and yield,
5	Water Users Association	2	Leaders	Water allocation, water fee
6	Irrigation Schemes	4	Leaders	Water allocation, types of farming practices
7	Village Government	5	Village Executive Officers	Water allocation, Demography
8	Ward Government	2	Ward Executive Officers	Demography, types of farming
9	Total	21		

Appendix 9: Average monthly water inflow to the Kihansi reservoir (m3/s)

Mon/Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
January	9.54	10.34	10.34	11.27	13.17	13.56	15.25	8.11	14.90	13.79	16.23	14.50
February	15.50	11.17	10.66	10.21	11.31	14.81	16.70	10.51	12.78	16.27	23.45	12.99
March	16.66	13.46	12.36	22.96	15.08	20.05	15.53	14.84	14.13	13.64	21.86	12.21
April	24.87	32.98	15.70	27.84	39.01	27.62	33.42	34.43	22.57	22.79	25.64	30.19
May	28.99	26.85	16.53	25.13	38.22	26.71	22.21	34.73	21.11	47.13	23.99	26.00
June	19.60	16.52	12.26	16.24	24.61	17.69	16.14	20.49	15.54	26.07	16.66	17.16
July	16.27	13.32	10.21	13.66	18.26	14.47	13.83	15.74	13.11	19.04	15.98	13.99
August	13.65	11.51	9.10	11.88	15.29	12.49	12.29	13.70	11.22	15.34	13.70	12.37
September	11.78	10.60	7.48	9.95	-	10.93	10.69	11.94	11.44	13.32	11.91	10.80
October	10.21	10.38	6.44	9.71	12.57	9.36	9.20	10.14	9.42	14.31	10.54	9.30
November	9.92	8.88	6.83	7.64	12.15	10.41	8.12	9.57	8.13	11.20	9.42	7.91
December	9.43	12.07	6.66	9.99	11.51	9.65	7.48	13.98	11.90	14.42	9.88	7.93

Appendix 10: Average monthly turbine discharge for the Kihansi reservoir (m³/s)

Mon/Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
January	11.09	8.34	8.34	9.63	11.31	11.79	13.30	7.00	13.47	11.79	14.44	12.68
February	12.98	9.23	8.84	8.81	9.51	12.70	15.04	8.91	10.81	14.28	17.35	11.28
March	14.82	11.56	10.74	21.40	13.09	16.33	13.45	12.54	12.49	11.65	15.84	10.43
April	19.93	20.68	13.62	21.85	20.30	22.09	21.01	21.47	18.80	18.33	15.45	21.16
May	20.51	20.30	14.85	21.23	22.75	21.48	18.78	36.64	19.16	22.96	15.09	20.47
June	17.65	14.94	10.54	14.60	21.51	15.65	13.95	17.79	13.56	21.96	10.55	15.05
July	14.10	11.52	8.22	11.25	16.14	12.60	11.50	13.06	11.24	16.61	13.53	11.78
August	11.66	9.47	7.72	9.86	13.19	10.45	9.97	11.02	9.27	13.26	11.53	10.30
September	10.03	10.60	6.40	8.20		7.21	8.66	9.34	9.41	11.19	9.72	8.19
October	8.37	8.37	5.62	8.02	10.41	7.16	7.47	7.99	7.56	12.19	8.63	7.56
November	8.47	6.90	5.36	6.53	10.11	8.42	6.31	7.70	6.79	9.22	7.52	6.40
December	7.57	10.14	5.98	8.36	9.66	7.81	6.15	11.90	9.35	12.41	8.15	6.49

Appendix 11: Average monthly power generation (kWh) for the Kihansi plant

Mon/Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
January	66.90	47.10	58.66	52.87	62.99	65.34	73.76	37.51	74.62	66.21	79.85	70.28
February	65.86	47.19	45.38	44.01	47.49	63.57	77.72	44.62	54.10	71.26	89.95	56.46
March	83.30	65.25	59.89	97.46	72.62	90.49	74.77	69.51	69.25	64.55	87.79	57.66
April	107.37	111.73	73.90	117.42	109.20	118.51	113.37	115.14	100.85	98.35	82.87	113.51
May	113.91	112.21	82.57	116.16	126.33	119.03	104.08	116.39	106.18	127.25	83.67	113.52
June	95.25	80.86	57.35	78.32	115.41	83.93	74.83	95.41	72.72	117.75	56.61	80.73
July	80.03	64.52	46.51	64.56	89.44	69.85	63.72	72.41	62.29	92.09	75.00	65.27
August	64.96	54.03	41.84	54.58	73.07	57.60	55.29	62.21	51.43	73.50	63.92	57.07
September	54.16	48.85	33.77	43.71	-	38.79	46.49	50.28	50.59	60.03	52.13	43.95
October	46.40	46.82	31.63	44.88	57.71	41.21	41.43	44.27	41.90	67.53	47.82	41.88
November	46.54	38.75	28.48	35.33	54.20	45.17	34.28	41.30	36.44	49.48	41.55	34.32
December	42.64	56.90	32.91	46.34	53.53	43.29	34.10	65.96	51.89	68.57	45.20	35.98

Appendix 12: Average monthly evaporation (mm) in Udzungwa Escarpment

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	147.98	132.55	147.17	131.52	118.92	109.65	118.98	141.03	168.40	200.92	193.72	175.87
2011	156.20	131.20	142.60	120.93	119.18	113.05	127.93	146.15	163.35	196.25	187.03	159.87
2012	144.68	140.92	139.37	124.28	119.00	112.58	127.10	150.30	173.22	199.63	176.57	166.20
2013	146.70	138.82	146.13	126.78	122.20	117.12	127.65	148.88	177.42	195.43	194.07	174.43
2014	140.88	127.75	138.07	120.30	116.45	107.77	120.02	144.28	162.60	183.12	180.08	169.67
2015	139.90	133.80	141.47	125.75	121.37	117.87	128.45	149.43	172.72	191.58	172.82	159.88
2016	135.90	134.90	145.23	117.17	115.83	107.70	117.68	141.22	166.60	195.25	191.70	176.15
2017	154.27	133.07	134.15	119.48	113.43	106.58	119.05	132.30	160.13	189.90	174.90	163.43
2018	133.40	138.12	134.20	121.47	115.65	104.52	108.07	141.87	163.42	178.92	177.45	161.30
2019	150.83	131.35	145.65	122.28	112.58	112.57	126.12	148.20	164.67	178.80	175.10	150.22
2020	138.77	134.13	132.55	118.17	116.22	103.83	104.78	133.47	157.37	180.28	173.32	159.37

Appendix 13: Average annual production data for Sugarcane in KSCL Plantations

Year	Water Use (m³)	Area (Ha)	Production (Tonnes)	Value of Cane (USD)	Production Cost (USD)
2015	29 606 397	5672.06	457 019	11 730 890	4 913 143
2016	61 337 569	6047.01	495 356	12 714 935	5 237 919
2017	29 548 743	5984.51	520 897	13 370 517	5 183 782
2018	36 236 260	5522.95	452 519	11 615 384	4 783 984
2019	28 933 123	5304.33	422 388	10 841 976	4 594 616
2020	37 401 014	5695.46	505 059	12 963 991	4 933 414
2021	53 794 524	5452.37	427 493	10 972 991	4 722 849
Average	39 551 090	5668.39	468 676	12 030 098	4 909 958

Appendix 14: Average production data for sugarcane for small-holder farmers

Year	Water Use (m³)	Area (Ha)	Production (Tonnes)	Value of Cane (USD)	Production Cost (USD)
2015	57 808 915	11 535.86	452 970	11 626 951	7 173 189
2016	61 233 085	11 702.45	468 098	12 015 263	7 647 362
2017	62 060 304	11 860.55	486 282	12 482 021	7 568 321
2018	55 963 811	15 695.43	427 817	10 981 317	6 984 616
2019	50 533 741	12 990.99	405 622	10 411 610	6 708 139
2020	49 006 569	13 287.37	477 656	12 260 598	7 202 784
2021	51 816 044	16 244.19	406 012	10 421 621	6 895 359
Average	55 488 924	13 330.98	446 351	11 457 055	7 168 539

Notes: Volume of water used is a summation of water use permit from RBWB

Appendix 15: Compilation of economics of Paddy Production in the study area

Years	Production (Tonnes)	Prices (US\$/Tonne)	Revenue (US\$)	Expenditure (US\$)	Profit (US\$)	Water Use (m ³)	PWP (Kg/m ³)	EVW (US\$/m ³)	ΔProfit (US\$)	ΔWater use (m ³)	MVP (US\$/m ³)
2010	239 332	267.80	64 093 110	63 009 686	1 083 424	737 678 261	0.32	0.001	1 083 424	737 678 261	0.001469
2011	227 430	271.10	61 656 273	60 652 674	1 003 599	711 804 348	0.32	0.001	-79 825	-25 873 913	0.003085
2012	211 202	269.14	56 842 906	55 678 341	1 164 565	676 526 087	0.31	0.002	160 966	-35 278 261	-0.00456
2013	299 851	274.00	82 159 174	80 474 568	1 684 606	869 241 304	0.34	0.002	520 041	192 715 217	0.002698
2014	442 739	274.41	121 492 009	119 986 470	1 505 539	960 302 174	0.46	0.002	- 179 067	91 060 870	-0.00197
2015	499 354	273.75	136 698 158	126 867 532	9 830 626	1 079 030 435	0.46	0.009	8 325 087	118 728 261	0.070119
2016	452 834	273.70	123 940 556	113 834 567	10 105 989	975 725 217	0.46	0.010	275 364	-103 305 217	-0.00267
2017	593 812	280.00	166 267 360	137 255 872	29 011 488	1 073 504 348	0.55	0.027	18 905 499	97 779 130	0.193349
2018	504 364	274.00	138 195 626	108 580 112	29 615 514	869 486 087	0.58	0.034	604 026	-204 018 261	-0.00296
2019	519 093	274.80	142 646 756	131 638 765	11 007 991	1 128 463 043	0.46	0.010	-18 607 523	258 976 957	-0.07185
2020	581 969	275.00	160 041 585	131 538 987	28 502 598	1 047 759 565	0.56	0.027	17 494 607	-80 703 478	-0.21678
2021	502 253	275.10	138 169 800	126 606 222	11 563 578	1 087 506 522	0.46	0.011	-16 939 020	39 746 957	-0.42617

Appendix 16: Compilation of economics of Sugarcane Production in the study area

Years	Production (Tonnes)	Prices (US\$/Tonne)	Revenue (US\$)	Expenditure (US\$)	Profit (US\$)	Water Use (m³)	PWP (Kg/m³)	EVW (US\$/m³)	ΔProfit (US\$)	ΔWater use (m³)	MVP (US\$/m³)
2010	790 534	26.60	21 028 204	10 023 322.82	11 004 882	145 425 692	5.44	0.076	11 004 882	145 425 692	0.075674
2011	822 026	26.60	21 865 892	11 775 281.65	10 090 610	147 848 154	5.56	0.068	- 914 272	2 422 462	-0.37741
2012	972 444	25.80	25 089 055	19 352 103.20	5 736 952	151 726 462	6.41	0.038	- 353 658	3 878 308	-1.12257
2013	847 726	25.80	21 871 331	11 168 599.95	10 702 731	157 517 385	5.38	0.068	4 965 779	5 790 923	0.857511
2014	907 748	25.80	23 419 898	11 302 754.17	12 117 144	146 749 846	6.19	0.083	1 414 413	-10 767 538	-0.13136
2015	909 989	25.67	23 357 841	10 136 197.42	13 221 644	146 922 255	6.19	0.090	1 104 499	172 409	6.406265
2016	1 036 541	25.67	26 606 214	984 520.00	25 621 694	151 034 960	6.86	0.170	12 400 051	4 112 705	3.01506
2017	907 179	25.67	23 285 713	917 654.00	22 368 059	146 706 100	6.18	0.152	-3 253 636	- 4 328 860	0.751615
2018	980 336	25.67	25 163 527	998 546.00	24 164 981	160 025 874	6.13	0.151	1 796 922	13 319 774	0.134906
2019	1 088 010	25.67	27 927 333	9 772 642.00	18 154 691	156 000 803	6.97	0.116	-6 010 290	- 4 025 071	1.493213
2020	1 048 271	25.67	26 907 296	9 462 819.00	17 444 477	152 516 555	6.87	0.114	-710 214	-3 484 248	0.203836
2021	933 505	25.67	23 961 438	8 996 284.00	14 965 154	156 423 432	5.97	0.096	-2 479 324	3 906 877	-0.63461

Appendix 17: Compilation of economics of HEP Production in the study area

Years	Production (kWh)	Prices (US\$/Tonne)	Revenue (US\$)	Expenditure (US\$)	Profit (US\$)	Water Use (m ³)	PWP (kWh/m ³)	EVW (US\$/m ³)	ΔProfit (US\$)	ΔWater use (m ³)	MVP (US\$/m ³)
2010	867 315 880	0.10	89 472 777	10 193 101.20	79 279 676	414 148 494.28	2.09	0.19	79 279 676	414 148 494.28	0.191428
2011	774 215 500	0.10	79 868 491	9 098 942.06	70 769 549	374 798 662.64	2.07	0.19	-8 510 127	-39 349 832	0.216268
2012	592 882 130	0.10	61 162 042	6 967 827.63	54 194 215	281 240 927.17	2.11	0.19	-16 575 334	- 93 557 735	0.177167
2013	795 648 690	0.10	82 079 551	9 350 834.92	72 728 716	395 757 548.29	2.01	0.18	18 534 501	114 516 621	0.16185
2014	861 991 900	0.10	88 923 553	10 130 531.30	78 793 021	417 482 428.44	2.06	0.19	6 064 305	21 724 880	0.279141
2015	836 770 700	0.10	86 321 720	9 834 119.98	76 487 600	405 088 835.56	2.07	0.19	-2 305 421	- 12 393 593	0.186017
2016	793 834 056	0.10	81 892 352	9 329 508.49	72 562 844	384 411 298.15	2.07	0.19	-3 924 756	- 20 677 537	0.189808
2017	815 021 500	0.10	84 078 061	9 578 513.23	74 499 547	437 095 378.15	1.86	0.17	1 936 703	52 684 080	0.036761
2018	772 246 220	0.10	79 665 339	9 075 798.16	70 589 541	374 395 768.23	2.06	0.19	-3 910 006	- 62 699 610	0.062361
2019	956 577 470	0.10	98 681 051	11 242 145.08	87 438 906	463 424 987.70	2.06	0.19	16 849 365	89 029 219	0.189257
2020	806 346 431	0.10	83 183 136	9 476 559.76	73 706 576	390 496 638.69	2.06	0.19	-13 732 330	-72 928 349	0.188299
2021	770 631 000	0.10	79 498712	9 056 815.34	70 441 897	373 853 376.68	2.06	0.19	-3 264 679	-16 643 262	0.196156

Appendix 18: Average annual value of inputs of production - based on 1 ha of farming.

N	Farming Inputs	Irrigated SRI	Rainfed SRI	Irrigated CTFS	Rainfed CTFS
A. Land Input					
1	Renting a farm	188.23	161.34	111.77	107.75
Sub Total A		188.23	161.34	111.77	107.75
B. Labor Inputs					
2	Farm Clearing	53.78	43.02	35.65	32.65
3	Ploughing	64.54	64.54	56.85	59.54
4	Blocks preparation	53.93	53.78	37.65	32.27
5	Nursery preparations	26.89	26.86	21.51	13.44
6	Watering the farm	48.40	-	43.02	-
7	Field leveling	80.67	72.60	63.66	64.54
8	Uprooting seedlings	37.65	43.02	26.39	24.20
9	Rice transplanting	86.40	86.05	58.02	59.54
10	Weeding with chemicals	64.54	96.80	64.43	53.35
11	2 nd Weeding manual	59.16	75.29	59.16	48.40
12	Bird control	86.05	69.91	53.78	-
13	Harvesting	46.25	64.54	64.54	80.67
14	Threshing	89.81	93.04	103.79	127.52
15	Winnowing	32.54	48.94	81.48	57.01
Sub Total B		830.59	838.40	769.91	653.10
B. Capital Inputs					
16	Seeds	16.13	13.60	19.41	14.03
17	Initiation fertilizer	13.44	35.33	14.68	33.40
18	Pesticides /Insecticides	6.45	5.92	8.07	5.38
19	Weeding chemicals	29.58	30.65	29.58	34.96
20	Boosting fertilizer	91.43	40.33	21.51	14.99
21	Pesticides /Insecticides	6.45	5.92	8.07	5.38
22	Panicle initiation fertilizer	5.93	5.38	27.27	14.99
23	Transportation costs	70.99	116.16	82.82	127.46
24	Storage	34.42	32.27	41.95	32.27
Sub Total C		275	286	253	283
Grant Total Paddy		1293.64	1285.30	1135.02	1043.70
Grant Total Rice		1387.76	1374.04	1236.13	1232.46

*All valued are converted to US\$ with a rate of TZS 2297.39 for 1 US\$ at Bank of Tanzania (BoT) rates on 5th Jan 2021 (<https://www.bot.go.tz/>).

RESEARCH OUTPUTS

(i) Publications

Sigalla, O. Z., Tumbo, M., & Joseph, J. (2021). Multi-stakeholder platform in water resources management: A critical analysis of stakeholders' participation for sustainable water resources. *Sustainability*, 13(16), 9260. DOI: <https://doi.org/10.3390/su13169260>.

Sigalla, O. Z., Kadigi, R. M. J., & Selemani, J. R. (2022). Assessment of variation in marginal productivity value of water in paddy farming systems in times of water stress. *Water*, 14(21), 3459. DOI: <https://doi.org/10.3390/w14213459>.

Sigalla, O. Z., Valimba, P., Selemani, J. R., Kashaigili, J. J., & Tumbo, M. (2023). Analysis of spatial and temporal trend of hydro-climatic parameters in the Kilombero River Catchment, Tanzania. *Scientific Reports*, 13(1), 7864. DOI: <https://doi.org/10.1038/s41598-023-35105-8>.

Sigalla, O. Z., Twisa, S., Chilagane, N. A., Mwabumba, M. F., Selemani, J. R., & Valimba, P. (2024). Future Trade-Off for Water Resource Allocation: The Role of Land Cover/Land Use Change. *Water*, 16(3), p.493. DOI: <https://doi.org/10.3390/w16030493>.

(ii) Poster presentation