Exploring Forest-Water Nexus in a Changing Environment of Kafue River Basin, Zambia

By

Muyaka Kamamba

A dissertation submitted to the University of Zambia in fulfilment of the requirement for the award of a Master of Science in Integrated Water Resources Management.

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DECLARATION

This dissertation was submitted in accordance with the Master of Science in Integrated Water Resources Management regulations at the University of Zambia. It has not been presented for any degree at this or any other university. All referenced work is acknowledged. Conducted under the O.R. Tambo Africa Research Chairs Initiative (ORTARChI), chaired by Prof. Imasiku Nyambe at the IWRM Centre, Geology Department, School of Mines, it was supervised by Prof. Kawawa Banda, Prof. Henry Sichingabula and Prof. Imasiku Nyambe.

Muyaka Kamamba **Signature: ……..**

Date: ……12th March, 2025….

APPROVAL

This dissertation of Muyaka Kamamba (ID: 22000448) is approved as fulfilling the requirements for the award of the Degree of Master of Science in Integrated Water Resources Management of the University of Zambia.

1. Internal Examiner 1:	**Signature**:	**Date:**
Dr. Manoah Muchanga	…….	……..
2. Internal Examiner 2:	**Signature**:	**Date**:
Dr. Mulenga Kalumba	…….	……..
3. External Examiner:	**Signature**:	**Date**:
Prof. Gretcen Gettel	…….	……..
4. Chairperson:	**Signature**:	**Date**:
Dr. Victor Mutambo	…….	……
5. Principal Supervisor:	**Signature:**	**Date**:
Prof. Imasiku Nyambe	……	……
6. Co-Supervisor:	**Signature:**	**Date**:
Prof. Kawawa Banda	…….	……

ABSTRACT

Water insecurity in Zambia's Kafue River Basin (KRB) is rising due to climate change, land-use change and increased water abstraction. The role of forests in the hydrological cycle, particularly through evapotranspiration (ET) has not been adequately explored. This study addressed this gap. The main objective was to explore the forest-water nexus in the Upper Kafue River Sub-Basin (UKRSB), its implications for sustainable river basin management and Inter-Basin Water Transfer (IBWT) from Luapula River Basin to KRB, Zambia. A systematic literature review using PRISMA guidelines was conducted through Google Scholar (1970 to 2023). Remote sensing datasets: Actual ET (AET), NDVI, Total Canopy Cover and Tree Density were acquired and processed. In combination with forest inventory procedures. Data was analysed using QGIS for spatial analysis and Microsoft Excel version 2108 for statistical analysis. Twenty-five relevant papers on the forest-water nexus were identified, indicating limited research on this topic. A bibliometric analysis highlighted small co-author clusters with prominent figures like Paletto and Springgay suggesting limited collaboration. Indirect field observations emphasised the significance of riparian forests and *Nymphaeaceae* (water lilies) in stabilising riverbanks and reducing stream turbidity respectively. AET in 2022 ranged from 268 mm year^{-1} to 1505 mm year^{-1}, with an annual average of 985 mm year^{-1}. Correlation between AET and NDVI varies with season, moderate during the dry season ($r^2 = 0.48$) and weaker in the wet season ($r^2 = 0.32$). Long-term trends (2009-2022) showed a decline in AET with a slope of -12.14, suggesting climatic changes or deforestation. A threshold AET rate of 80 mm month^{-1} was observed from 2013 to 2022. To offset water loss seasonal variations, an annual requirement of 4.36 billion m^3 is needed. The Kalahari Woodland land cover (1177 mm year^{-1}) had the highest AET rate, whereas Miombo/Chipya (1082 mm year^{-1}), Parinari (1005 mm year^{-1}) and Munga (1005 mm year^{-1}) woodlands showed lower rates. Species-wise, *Julbernardia globiflora* (1444.6 mm year^{-1}) exhibited the highest AET rate in the Kalahari Woodland. *Pinus kesiya* and *Eucalyptus grandis* plantations also demonstrated elevated AET rates both at 1280 mm year^{-1}. For these reasons, there is need for considering land cover types and species-specific ET rates in IBWT planning to mitigate water loss. Necessitating integrated river basin and forest management strategies aimed at water conservation in the KRB. Future research should determine tree age effects on ET and employ sap flow meters for species-specific ET estimation. Collaboration among forestry and water institutions is necessary to enhance policy and management strategies.

DEDICATION

Dedicated to the guardians of our natural world, whose tireless efforts in preserving and understanding the delicate balance between forests and water inspire us to strive for a sustainable future.

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This thesis was undertaken within the framework of the O.R. Tambo Africa Research Chairs Initiative (ORTARChI) chaired by Professor Imasiku Nyambe at the IWRM Centre, Geology Department, School of Mines, University of Zambia. Whose overall objective were to contribute to improving water management in the Kafue River Basin and Luapula River Basin in the framework of IWRM by creating knowledge through studies on the water and stream sediments quality, quantity, inter-basin water transfers between the two basins (SDG 6 – Water and Sanitation) and development of site-specific remediation technologies. I extend my sincere gratitude to the ORTARChI project for their generous funding, which made this research on the Forest-Water Nexus in the Kafue River Sub-Basin possible. Their commitment to supporting scientific inquiry was instrumental in advancing our understanding of the critical relationship between forests and water resources. I would also like to acknowledge the invaluable partial funding received from WaterNet. This support contributed to the success of this research. WaterNet's dedication to fostering knowledge and capacity building in the water sector is commendable and I am honoured to have been a beneficiary of their support. Furthermore, I wish to express my appreciation to all the individuals, organisations and communities in the Kafue River Basin who generously shared their knowledge and resources, making this research a collaborative endeavour. Their contributions were invaluable to the completion of this work. I am deeply grateful to my supervisors and colleagues who provided unwavering support throughout the journey.

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LIST OF SYMBOLS

Symbols	Description	Unit
R_n	Net radiation	Watts per square meter (w/m²)
G	Soil heat flux	Watts per square meter (w/m²)
H	Sensible heat flux	Watts per square meter (w/m²)
LE	Latent heat flux	Watts per square meter (w/m²)
Rah / r_{av}	Aerodynamic resistance	Seconds per meter (s/m)
ΔT	Near-surface temperature difference	Kelvin
Cp	Specific heat capacity of air	Joules per kilogram per Kelvin (J/[kg·K])
ρ	Density of air	kilograms per cubic meter (kg/m³)
TS	Surface temperature	Kelvin
α	Albedo	Unitless
$NDVI$	Normalised Difference Vegetation Index	Unitless
$\varepsilon 0$	surface thermal emissivity	Unitless
$RS\downarrow$	Incoming shortwave radiation	Watts per square meter (w/m²)
$RL\downarrow$	Incoming longwave radiation	Watts per square meter (w/m²)
$RL\uparrow$	Outgoing longwave radiation	Watts per square meter (w/m²)
P	Precipitation	Millimetres (mm)
I	Inflow	Millimetres (mm)
ET	Evapotranspiration	Millimetres (mm)
ΔS	Change in soil water content	Millimetres (mm)

$\triangle G$	Change in groundwater storage	Cubic metres (m^3)
$\triangle W$	Change in surface water storage	Cubic metres (m^3)
λE	Potential evapotranspiration	Millimetres (mm)
β	Bowen ratio	Unitless
γ	Psychometric constant	kilopascals per degree Celsius (kPa/°C)
Δe	Change in water vapour pressure	Kilopascals (kPa)
r_s	Canopy surface resistance	Seconds per meter (s/m)
e_a	Mean daily ambient vapour pressure	Kilopascals (kPa)
e_s°	Mean saturated vapour pressure	Kilopascals (kPa)
H	Height	Metres (m)

ACRONYMS AND ABBREVIATIONS

ACAPS	Assessment Capacities Project
AET	Actual Evapotranspiration
AI	Aridity Index
CDC	Centres for Disease Control and Prevention
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CIFOR	Centre for International Forestry Research
CLs	Confidence Intervals
DBH	Diameter at Breast Height
EC	Eddy Covariance
ECZ	Environmental Council of Zambia
EIA	Environmental Impact Assessment
ELCA	Ecosystem and Land Cover Assessment
Eq	Equation
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
ETM+	Enhanced Thematic Mapper Plus
EVI	Enhanced Vegetation Index
eWEF	Enhanced Water Energy Food
FAO	Food and Agriculture Organisation
GEE	Google Earth Engine
geeSEBAL	Google Earth Engine Surface Energy Balance Algorithm for Land
GHG	Greenhouse gas
GIS	Geographical Information System
GLEAM	Global Land Evaporation Amsterdam Model
GPS	Global Positioning System
IAPs	Invasive Alien Plants
IBWT	Inter-Basin Water Transfer
ICRAF	International Council of Research in Agroforestry
IMF	International Monetary Fund
IR	Thermal-infrared
ITCZ	Inter Tropical Convergence Zone
IWRM	Integrated Water Resources Management

JICA	Japan International Cooperation Agency
LAI	Leaf Area Index
LRB	Luapula River Basin
LST	Land Surface Temperature
LULC	Land-Use/Land-Cover
MARD	Ministry of Agriculture and Rural Development The Socialist Republic of Vietnam
METRIC	Mapping Evapotranspiration at high Resolution with Internalised Calibration
MEWD	Ministry of Energy and Water Development
MOD 16	Moderate-resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalised Difference Vegetation Index
NIR	Near Infare Red
OLI	Operational Land Imager
ORTARChI	O.R. Tambo Research Africa Chair Initiative
PET	Potential Evapotranspiration
PM	Penman-Monteith
PRISMA	Preferred Reporting Items for Systematic Reviews
PT	Priestley-Taylor
PT-JPL	Priestley-Taylor Jet Propulsion Lab
P-Value	Probability Value
QGIS	Quantum Geographic Information System
RCMRD	Regional Centre for Mapping of Resources for Development
RIS	Research Information Systems
RS	Remote Sensing
SEB	Surface Energy Balance
SEBAL	Surface Energy Balance Algorithm for Land
SEBI	Surface Energy Balance Index
SEBS	Surface Energy Balance System
SSEBop	Operational Simplified Surface Energy Balance
TCC	Total Canopy Cover
TIRS	Thermal Infrared Sensor
TSEB	Two-Source Energy Balance

UKRSB	Upper Kafue River Sub-Basin
UN	United Nations
UNEP	United Nations Environment Programme
UNZA	University of Zambia
VOSviewer	Visualisation Of Similarities Viewer
WaPOR	Water Productivity Open-Source Portal
WARMA	Water Resources Management Authority
WaSSI	Water Supply Stress Index
WBG	World Bank Group
WEAP	Water Evaluation and Planning
WEF	Water Energy Food
WL	Woodlands
WL1	Parinari Woodland
WL2	Munga Woodland
WL3	Miombo/Chipya Woodland
WL4	Kalahari Woodland
WWF	World Wide Fund for Nature
ZAFFICO	Zambia Forestry and Forest Industries Corporation
ZamStats	Zambia Statistics Agency

CHAPTER ONE: INTRODUCTION

1.1 Background

In a world grappling with the impacts of climate change and escalating environmental degradation, the interplay between forests and water resources has emerged as a focal point of scientific inquiry and policy discourse (Calder et al., 2007; FAO, 2019; Zhang et al., 2022). This nexus, fundamental to the functioning of terrestrial ecosystems and the provision of ecosystem services holds particular significance in regions where water scarcity and ecological vulnerability intersect (Springgay et al., 2019).

Forests, with their canopy structures and root systems play a fundamental role in regulating the water cycle (Mauser, 2021). Through processes such as interception, infiltration and transpiration, forests influence the distribution, quality and quantity of water resources within landscapes (Roberts, 2009). They act as natural sponges, absorbing rainfall and reducing surface runoff, thus mitigating the risk of floods and soil erosion (Bahmud & Mohammed, 2023; Mauser, 2021). Forests contribute to groundwater recharge by allowing rainwater to percolate into aquifers, ensuring a steady supply of freshwater for both natural and human systems (FAO & CIFOR, 2005). In return, water availability and quality play a role in determining the health and productivity of forest ecosystems (Shah et al., 2022).

The role of forests in regulating the water cycle extends beyond hydrological processes. Forests also provide a myriad of ecosystem services that directly impact human well-being and livelihoods (UNEP, 2015). These ecosystem services, categorised into provisioning, supporting, regulating and cultural services (Table 1.1) underscore the multifaceted contributions of forests to water resources and broader socio-ecological systems (World Resources Institute, 2005). Provisioning services encompass the tangible benefits including food, raw materials and freshwater resources (Kalaba et al., 2013). Forests serve as sources of nourishment, yielding fruits, nuts and other edible products essential for human sustenance (Chileshe, 2001; Jamnadass et al., 2015). They provide raw materials such as fuelwood and fibre supporting various industries and livelihoods (Vinya et al., 2011). Supporting services encompass the ecological functions that underpin ecosystem structure and function, fostering resilience and biodiversity (Brander et al., 2023). Forests serve as habitats for diverse plant and animal species maintaining genetic diversity and ecological balance

(Burley, 2002). Additionally, they facilitate nutrient cycling and soil formation enriching soils and sustaining productivity over time (Johnson & Turner, 2019). Regulating services represent the regulatory functions which contribute to environmental stability and resilience (World Resources Institute, 2005). Forests play a role in local climate regulation influencing temperature, humidity and precipitation patterns through evapotranspiration (ET) and atmospheric moisture recycling (Ellison et al., 2017). Furthermore, cultural services encompass benefits which contribute to human well-being and cultural identity (UNEP, 2015). They provide recreational opportunities offering spaces for leisure activities, nature appreciation, mental and physical health benefits (Atalay et al., 2024). They also attract tourists, supporting local economies and cultural heritage (Chomba & Sianjobo, 2014; Kabeta & Chikwanda, 2023). They inspire artistic expression, cultural traditions and spiritual connections to nature fostering a sense of place and belonging within communities (Brown & Verschuuren, 2018).

Table 1.1: Water ecosystem services provided by forests (World Resources Institute, 2005). Highlighting those related to water ecosystems.

Provisioning Services	**Regulating Services**	**Cultural Services**
• Food	• Local climate air quality	• Recreation, mental and physical health
• Raw materials (fuel wood and fibre)	• Water purification	• Tourism
• Freshwater	• Carbon sequestration and storage	• Aesthetic appreciation and inspiration for culture, art and design
• Medicinal resources	• Moderation of extreme events	• Spiritual experience and sense of place
Supporting Services	• Biological control	
• Habitat for species	• Erosion prevention and maintenance of soil fertility	
• Maintenance of genetic diversity	• Pollination	
• Nutrient cycling	• Regulation of water flow	
• Soil formation		

Forests do indeed contribute to regulating the water cycle and providing various ecosystem services, it's important to also acknowledge the equally indispensable role of water itself in

maintaining forests and supporting a diverse array of life forms. Water, as a primary driver of ecosystem functioning, directly influences the health, productivity and resilience of forest ecosystems (Esquivel et al., 2020). It's a fundamental requirement for the growth and survival of trees and other vegetation (McElrone et al., 2013). Through the process of photosynthesis, plants utilise water to produce energy and synthesise organic compounds enabling them to grow, reproduce and fulfil their ecological functions (Kameoka & Hashimoto, 2018). Adequate water availability is therefore essential for maintaining the structural integrity and biodiversity of forests, supporting diverse fauna and flora across various habitats and ecosystems.

In shaping the physical and chemical properties of soils, which serve as the foundation for forest ecosystems, water is required (Schoenholtz et al., 2000). Adequate soil moisture levels facilitate nutrient uptake and root development, supporting healthy plant growth and productivity (Li et al., 2009). Water regulates soil temperature and pH, influences nutrient availability and mediates biogeochemical processes such as mineral weathering and decomposition (Duckworth et al., 2014). Beyond its role in supporting individual trees and soils, water also governs broader hydrological processes that drive ecosystem dynamics and landscape-level patterns. It serves as a medium for the transport of nutrients, sediments and organic matter within forest ecosystems, facilitating nutrient cycling, sedimentation and aquatic habitat formation (Shah et al., 2022). Riparian forests in particular, play a vital role in stabilising stream banks, filtering pollutants and providing habitat for aquatic species, thereby enhancing water quality and biodiversity in freshwater ecosystems (Dountchev et al., 2017). These ecosystem services are essential for supporting the ecological integrity and functioning of aquatic ecosystems, as well as the provision of clean water for human consumption and livelihoods. In essence, water is the lifeblood of forest ecosystems sustaining their structure, function and biodiversity.

Water can be transferred thousands of kilometres away to other regions through Inter-Basin Water Transfers (IBWT) to meet demand where supply is scarce (Liu et al., 2022). IBWT represents a solution to address the growing challenges of water scarcity in various regions but is often times a pipe-dream (Pittock et al., 2009). As global populations continue to rise, so does the demand for water for domestic, agricultural and industrial use. Coupled with the impacts of climate change, such as altered precipitation patterns and increased evaporation rates, many regions face significant water shortages.

Zambia, endowed with abundant water resources that underpin its economic development potential is nonetheless grappling with water scarcity challenges and recurring droughts in various regions including the Kafue River Basin (KRB) (ACAPS, 2024; MEWD, 2007; WWF, 2018). Covering 20% of Zambia's landmass, the KRB serves as a focal point for key economic activities such as mining and agriculture while also hosting approximately half of the country's population (Chomba & Nkhata, 2016; Denga et al., 2023; WWF, 2016). Kafue River is a significant tributary of the Zambezi River further emphasising its importance in Zambia's hydrological landscape (WWF, 2016). Recognising the critical importance of water resources in sustaining the basin's socio-economic activities and ecological integrity, The O.R. Tambo Research Africa Chair Initiative (ORTARChI) Project at the Integrated Water Resources Management (IWRM) Centre, University of Zambia (UNZA), embarked on a research endeavour (Lusaka Times, 2022). With a substantial grant of 27.6 million Zambian Kwacha, the initiative aimed to explore the feasibility of IBWT from the Luapula River Basin (LRB) to the KRB, offering a potential solution to alleviate water stress and revive the basin's ecological health (Lusaka Times, 2022). These pressures on water resources create a critical need for innovative and sustainable water management solutions. The broader context of this initiative highlights the complex interplay between various factors contributing to water scarcity. The project emphasised that while IBWT can be a vital tool for addressing regional water shortages, careful planning and management are essential to ensure that the transfer does not exacerbate existing problems or create new ones. Understanding the interconnectedness of ecosystems, land use and water resources is key to achieving sustainable outcomes with IBWT projects.

1.2 Problem Statement

In alignment with the project, it becomes imperative to understand the dynamics of the forest-water nexus within the KRB. Despite forests roles in regulating hydrological processes and sustaining ecosystem services, there exists a notable dearth of scientific studies examining the nexus in the KRB (Calder et al., 2007; Creed & Noordwijk, 2018; FAO, 2019; Zhang et al., 2022). Amidst discussions of IBWT and basin revitalisation efforts, misconceptions and myths persist regarding the relationship between forests and water, particularly concerning the water loss through ET (Hamilton et al., 2008). Moreover, the nexus is often unaccounted for in policy making and planning (Hamilton et al., 2008). Three-quarters of forests are not managed for soil and water

conservation, which poses a fundamental challenge to achieving sustainable and resilient communities and ecosystems (Abell et al., 2019; FAO, 2015). There is limited understanding of the actual water use by forests and how changes in forest cover may impact water resources (FAO, 2019). The lack of data on forest ET and its impact makes it difficult to support informed decisions on the sustainable management of water resources.

Forests play a crucial role in both the water and carbon cycles but with climate change their impact on the water cycle becomes just as critical as their role in the carbon cycle (Creed & Noordwijk, 2018; Ellison et al., 2017). Often dubbed the "lungs of the planet," also serve as its kidneys maintaining the Earth's ecological balance (Creed & Noordwijk, 2018). At the local level, water conservation often takes precedence over forests' role as carbon sinks, despite the public's emphasis on the latter (Creed & Noordwijk, 2018). Efforts to boost carbon storage through tree planting strategies focused solely on carbon may inadvertently affect water resources. In certain instances, the promotion of fast-growing tree species for carbon sequestration has been observed to detrimentally impact local water supplies (Creed & Noordwijk, 2018). This leaves us with the question of whether and which of our forest species have a negative impact on water resources and which ones do not (FAO, 2019). Therefore, the main objective of this research was to explore the forest-water nexus in the KRB, its implications for sustainable river basin management and Inter-Basin Water Transfer from Luapula River Basin to KRB, Zambia.

1.3 Research Objectives

The specific objectives aligning with main objective were as follows:

i. To establish/identify the current state of Knowledge regarding the Forest-Water Nexus in the KRB;

ii. To evaluate the spatial and temporal distribution patterns of ET in relation to water loss across different forest types and land cover classes; and

iii. To identify land cover and forest types/species with higher AET rates.

1.4 Research Questions

The general research question was: How does the relationship between forest ecosystems and water resources in the KRB impact sustainable river basin management?

The research answers the following specific questions:

i. What is the current state of knowledge regarding the forest-water nexus in the KRB, Zambia as evidenced by existing literature and research?

ii. How do spatial and temporal patterns of ET vary within the KRB and what factors contribute to these variations? and

iii. Which land cover, forest types or species in the KRB exhibit higher rates of ET and what are the ecological implications of their water loss to IBWT?

1.5 Significance of the Study

Elucidating the interactions between forests, water resources and land cover types in the UKRSB assumes paramount importance to ensuring ongoing guidance to effective river basin management strategies. The study's significance to the Government of the Republic of Zambia, especially within the context of the ORTARChI Project is offering an understanding of AET dynamics of various forest/woodland and their implications on water loss patterns in view of IBWT. This knowledge can guide the government in several key areas: Water Resource Management, Forest Conservation Policies, Climate Adaptation Plans, Sustainable Land Use Planning and in Research & Monitoring. The systematic literature review provides an overview of the current state of research, identifies gaps in knowledge and highlights key trends and patterns in the literature. Systematically reviewing the existing research, the study highlights areas where more investigation is needed and build upon the narrative literature review. By analysing the spatial and temporal patterns of ET across different forest types and land cover classes, the study provides critical insights into water loss in the UKRSB. When planning an IBWT it's important to understand how water is lost within the receiving basin. Knowing where and how water loss occurs helps identify areas with high ET rates and identify major land cover and forest species exacerbating this loss. Moreover, this information guides planners in deciding where to channel the transferred water to maximise its

effectiveness. It also helps determine how much water is needed to offset losses and meet the basin's needs. If planners don't understand where water is being lost, there's a risk that the IBWT could be failure. For example, if high ET rates are found in certain forest types or land cover, introducing more water to these areas without considering their needs could lead to faster depletion. Planners can ensure that the transferred water is distributed in a way that mitigates rather than aggravates water shortages. Additionally, forest ecosystems are sensitive to changes in water availability. If water transfers are not planned carefully, they could lead to unintended consequences such as altered forest growth, increased erosion or damage to habitats. This information is key for selecting priority areas for water management and conservation, allowing for a more targeted approach to minimise water loss. Essentially, land cover/forest types need to be accounted for in the water balance budget due different AET rates.

CHAPTER TWO: LITERATURE REVIEW

2.1 General Remarks

The background of the narrative literature review provides an overview of the topic under investigation, tracing the evolution of research and knowledge within the field.

2.2 Background

It is common knowledge that forests influence the hydrological cycle and that accordingly they have an effect on water resources both quantitatively and qualitatively (FAO, 2013; Owens & Lund, 2009; Wood et al., 2008). Forest hydrology is the scientific discipline that examines the interactions between forests and water resources (FAO, 2013; Kumagai et al., 2016). This field encompasses the study of water flows within forests, the influence of forests on water resources and the effects of changes in forest cover on hydrologic processes (Wood et al., 2008). The history of forest hydrology can be traced back to early studies in the early 1900s that examined water movements in forested landscapes, seeking to understand the distribution and availability of water resources (Sun et al., 2016). Over time, the scope of forest hydrology has broadened to encompass a wide range of topics including the effects of forest management practices on water quality and quantity, the influence of forests on climate and atmospheric processes, and the role of forests in regulating water-related ecological processes (FAO, 2019; Makarieva & Gorshkov, 2006). Today, forest hydrology is a critical component of broader efforts to understand and manage water resources in a changing world and is an important area of interdisciplinary research that draws on disciplines such as geology, ecology, climatology and hydrology (Creed & Noordwijk, 2018). Despite its significance, forest hydrology alone does not fully capture the broader socio-ecological and policy dimensions of forest-water interactions. This has led to the emergence of the forest-water nexus, which integrates the physical processes studied in forest hydrology with ecological, social and governance perspectives (Springgay et al., 2019).

2.3 The Forest-Water Nexus

The forest-water nexus refers to the interplay between forest ecosystems and water resources (Eberhardt et al., 2019; Springgay et al., 2019). This relationship has been the subject of research and analysis worldwide (Sanchez, 2018). The nexus highlights the critical ecosystem services that

forests provide, including precipitation interception, water storage and gradual release over time (Gerrits, 2010; Mendes et al., 2021;World Resources Institute, 2005). They also help to maintain soil moisture levels, reduce erosion and promote healthy water quality and quantity (Kučera et al., 2020). Thereby, an important factor in human societies' wellbeing and the environment (UNEP, 2015; World Resources Institute, 2005).

While forest hydrology primarily focuses on the physical interactions between forests and water, the forest-water nexus expands this understanding by incorporating the socioeconomic and ecological dimensions of forest-water interactions. It considers how forest conservation, land-use policies and human interventions shape water availability and ecosystem stability (Springgay et al., 2019). Research into the forest-water nexus has demonstrated significance on a global scale (Creed & Noordwijk, 2018). Numerous studies have investigated the effects of deforestation and forest degradation on water resources (Kasaro et al., 2019; Mompremier et al., 2022). In Africa, researchers have emphasised the importance of forests in maintaining water resources such as the Mau Forest Complex in Kenya and the Upper Tana River Basin in Ethiopia (Jacobs et al., 2007). Similarly, in Zambia, scholars have conducted research on the impact of deforestation on water resources, highlighting the role of forests in regulating streamflow and mitigating erosion (Kasaro et al., 2019; UNEP, 2015). In the past, policy decisions were often based on the assumption that increasing tree cover directly resulted in higher water availability (Calder et al., 2007; Kalaba, 2016). However, contemporary research challenges these views, leading to the development of three key theories that explain the relationship between forest cover and water yield: the Sponge Theory, Pump Theory and Trade-Off Theory (Eberhardt et al., 2019; FAO et al., 2021). These perspectives illustrate the complex interdependence between forests and hydrological processes, further reinforcing the necessity of an integrated forest-water nexus approach that balances hydrological science with ecological and policy considerations.

2.3.1 Sponge Theory

The Sponge theory suggests that forests act as sponges, retaining water during the wet season and releasing it slowly during the dry season (Blumenfeld et al., 2009; Peña-Arancibia et al., 2019).This helps to maintain stable water flows and reduce the risk of flooding and drought (Ellison et al., 2017). Forested areas are known to have a significant impact on water yield but the

exact mechanisms by which this occurs are not yet fully understood (Creed & Noordwijk, 2018; Hamilton et al., 2008). Forests are able to act as sponges due to the unique structure of their root systems which are able to hold onto water and prevent it from immediately flowing downstream (Peña-Arancibia et al., 2019). Additionally, the forest canopy is able to intercept rainwater, reducing the amount of water that reaches the ground and allowing more time for the water to be absorbed by the soil and vegetation (Creed & Noordwijk, 2018; Zhang et al., 2022).

The sponge theory has important implications for the management of forested areas, particularly in areas where water is a scarce resource (Blumenfeld et al., 2009). For example, in areas experiencing drought, preserving forested areas can help to maintain stable water flows and prevent water shortages (Mauser, 2021). Similarly, in areas experiencing flooding, preserving forested areas can help to absorb excess water and reduce the risk of damage from flooding (FAO & CIFOR, 2005). Despite the importance of the sponge theory, there are some limitations to its application. For example, the ability of forests to act as a sponge is dependent on a range of factors, including the type of vegetation, the topography of the area and the intensity of rainfall events (Bruijnzeel, 2004; Hamilton et al., 2008). The theory is also primarily applicable to small to medium-sized basins and may not be applicable to larger river basins (Creed & Noordwijk, 2018).

2.3.2 Pump Theory

The pump theory suggests that forests act as a pump, drawing water from the ground and releasing it into the atmosphere through ET (Jackson et al., 2005; Luedeling et al., 2019; Peña-Arancibia et al., 2019). In which, areas where trees consume significant amounts of water exacerbate local water scarcity leading to decreased stream flows and depleted groundwater levels (Jackson et al., 2005). The influence of trees and forests on water availability is significant both locally and regionally (Ellison et al., 2012; 2017). Various processes and mechanisms related to tree cover affect water availability although some remain poorly understood (FAO, 2019). Nonetheless, it's clear that there are discernible impacts which can often be detrimental. Dense plantations have been observed to contribute to reduce local stream flows and depleted groundwater levels compared (Luedeling et al., 2019). This perspective resonates with the evolving scientific understanding of tropical forest functioning as articulated by Hamilton & King (1983) who proposed that roots might be better described as a pump rather than a sponge (Bruijnzeel, 2004).

They emphasised that roots do not release water during the dry season but instead extract it from the soil to support tree transpiration and growth (Bruijnzeel, 2004; Hamilton et al., 2008). While discussing the pump effect, it's important to differentiate it from the biotic pump theory which was first proposed by Russian scientists Makarieva & Gorshkov (2007; 2010). They suggested that the evaporation of water from forests and other vegetation creates low-pressure zones that draw moist air from the ocean inland, leading to increased rainfall and water yield in the surrounding areas (downwind) (Makarieva & Gorshkov, 2006; 2010).

According to Ellison et al. (2017), the pump theory has major consequences for managing forest ecosystems and water resources. It suggests that certain forest covers, types or species may exacerbate water scarcity issues, necessitating exploration for better management strategies (FAO, 2019; Morokong et al., 2016). As temperatures rise, the negative impact of the pump effect on water resources may worsen (Hamududu & Ngoma, 2018). Climate change has brought increased attention to the pump theory in recent years (Creed & Noordwijk, 2018; Ellison et al., 2017). With elevated temperatures, the role of forests to water resources becomes increasingly crucial underscoring the necessity for further research into the mechanisms by which forests influence water yield (Creed & Noordwijk, 2018; Ellison et al., 2017; Mauser, 2021).

2.3.3 Trade-off Theory

The trade-off theory suggests that there is a trade-off between forest cover and water yield. As forests are cleared, water yield initially increases but then decreases over time as the land becomes more degraded (Calder, 2007; Ilstedt et al., 2016). This theory recognises that, the relationship between forests and water is complex and dependent on many factors including the type of vegetation, climate and topography (Calder et al., 2007; Hamilton et al., 2008). Increasing forest cover can lead to decreased water yield due to increased ET (Calder et al., 2007; Ellison et al., 2012). As the amount of vegetation in an area increases, the overall amount of ET also increases leading to a decrease in water yield (Ilstedt et al., 2016). Also, that forest cover can lead to changes in the water balance where more water is retained in the soil and vegetation resulting in less water flows downstream (Shah et al., 2022). The implications are that for in some cases, it may be necessary to balance the benefits of forest cover for ecosystem services such as carbon sequestration and habitat preservation against the potential negative impacts on water yield (Creed

& Noordwijk, 2018). There are also instances where augmenting forest cover can result in enhanced water yield including groundwater recharge and cloud formation. In areas experiencing erosion and soil degradation increasing forest cover can help to stabilise soils and increase water retention leading to an overall increase in water yield (Ellison et al., 2012; Zuazo & Pleguezuelo, 2008). The issue at hand is that forests are often viewed as a homogenous entity rather than as a collection of unique species with distinct characteristics (Ellison et al., 2012, 2017; FAO, 2019; Hamilton et al., 2008). Some species may exhibit behaviours in line with the sponge theory and others with the pump theory. It remains unclear which species in the UKRSB actually adhere to any of these theories, specifically by facilitating the release of water significantly higher than others into the atmosphere through ET (FAO, 2019).

2.4 Remote Sensing Technology

Across extensive geographic areas, Remote Sensing (RS) data is progressively employed for estimating total evaporation, commonly known as ET (Tran et al., 2023). This utilisation of RS technology, the process of collecting and interpreting information about the environment from a distance usually through the use of satellite or airborne sensors (Estes et al., 2001), has enabled researchers to monitor and analyse ET patterns with greater accuracy and spatial coverage. The technology involves capturing electromagnetic radiation reflected or emitted by the Earth's surface and analysing the data to create images or maps of various environmental features such as land cover, vegetation, water resources and atmospheric conditions (Estes et al., 2001). RS technology has become an important tool for a wide range of applications (Douna et al., 2021). It allows for the collection of information on large areas in a relatively short amount of time making it more efficient and cost-effective compared to traditional field-based methods (Estes et al., 2001; Schowengerdt, 2007).

There are two main types of RS technology: passive and active (Gupta et al., 2018). Passive sensors detect and measure natural radiation emitted or reflected by the Earth's surface such as visible, infrared and thermal radiation (Estes et al., 2001; Gupta et al., 2018). Active sensors, emit their own energy such as radar waves and measure the energy that is reflected back to the sensor (Gupta et al., 2018). Some of the commonly used RS technologies include:

i. Optical sensors, these sensors capture electromagnetic radiation in the visible, near-infrared and thermal-infrared portions of the spectrum (Estes et al., 2001). They are commonly used for vegetation mapping, land cover classification and monitoring changes in urban areas (Schowengerdt, 2007). Examples include multispectral, hyperspectral and ultra-spectral sensors;

ii. Radar sensors, use radar waves to create images of the earth's surface (Schowengerdt, 2007). They are particularly useful for mapping topography, detecting changes in land surface features and monitoring natural hazards such as floods and landslides (Schowengerdt, 2007); and

iii. Lidar sensors, use laser pulses to create detailed three-dimensional maps of the earth's surface (Estes et al., 2001). They are commonly used for mapping forests, wetlands and coastal environments (Schowengerdt, 2007).

2.4.1 Evapotranspiration

Evapotranspiration (ET), a complex hydrological process that denotes the cumulative movement of water from land surfaces to the atmosphere through plant transpiration and soil evaporation (Figure 2.1), is an important component of the global water cycle (Katul et al., 2012). It's a process that facilitates the regulation of water balance in diverse ecosystems worldwide (Raza et al., 2023). This occurs through the provision of a dynamic water balance mechanism that enables the movement of water into the atmosphere through plant and soil interactions (Ghiat et al., 2021; Katul et al., 2012). Plants take up water through their root system and release it into the atmosphere through stomata on their leaves (Chavarria & Pessoa-dos-Santos, 2012). On the other hand, soil evaporation is the process by which water evaporates from the soil surface (Kustas, 2020). The joint effects of these two processes lead to ET (Lawrence et al., 2007).

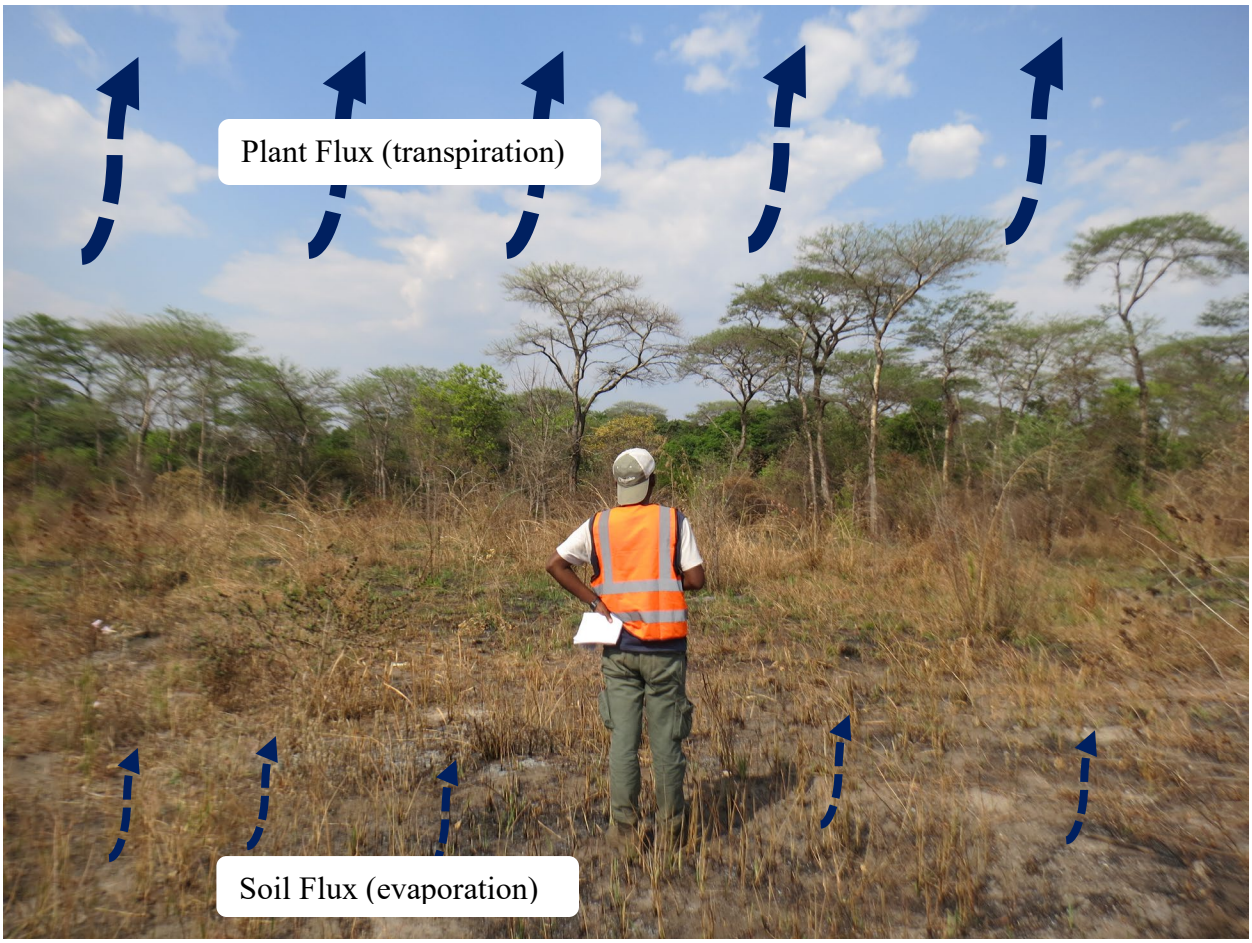

Figure 2.1: A snapshot from the Munga Woodland in the UKRSB, Mpongwe, Zambia. The blue (water vapour) Arrows illustrate the fluxes of evaporation from both the soil and the forest canopy.

The significance of ET cannot be overstated (Raza et al., 2023). This hydrological process plays a critical role in regulating regional and global climate, as it directly impacts the amount of water vapour in the atmosphere, which in turn influences precipitation patterns, cloud formation and temperature (Creed & Noordwijk, 2018). This process helps in maintaining soil moisture levels, thereby influencing plant growth, crop yields and overall ecosystem health (Corradini, 2014; Rasheed et al., 2022). Deviations from normal patterns of ET can serve as an indicator of ecosystem health as they could be a warning sign of environmental disturbances such as land-use changes, water depletion or climate change (Zhao et al., 2022).

2.4.2 Types of ET

There are three types of ET: Potential, Actual and Reference ET (Hasiotis, 2007; Irmak & Haman, 2003). Each type is defined by the different conditions under which it occurs and is useful for different purposes in water resource management (Samboko, 2016). Potential Evapotranspiration (PET) is the amount of water that could potentially evaporate and transpire from a given surface if there were no limitations on water availability (Hasiotis, 2007; Kirkham, 2023; Portela et al., 2019). It represents the maximum possible ET rate for a given area under specific climatic and vegetation conditions (Hasiotis et al., 2007; Kirkham, 2023). PET is often used as an indicator of the water demand of crops and other vegetation and is used to estimate irrigation water requirements (Kirkham, 2023). PET is typically estimated using empirical equations based on meteorological variables such as temperature, humidity, solar radiation and wind speed (Valipour, 2017). Actual Evapotranspiration (AET) is the actual amount of water that is lost from the land surface through evaporation and transpiration under existing soil moisture and plant water availability conditions (Hasiotis, 2007). AET represents the actual water demand of crops, other vegetations and is influenced by soil moisture, plant cover and climate conditions (Ochoa-Sánchez et al., 2019). It can be measured directly using field instruments such as lysimeters or estimated using RS data and modelling approaches (Phiri et al., 2013). It can be used to optimise irrigation and other water management strategies (Ochoa-Sánchez et al., 2019) like IBWT. Reference Evapotranspiration (RET) is the amount of water that would evaporate and transpire from a hypothetical reference crop (a well-watered, uniform and actively growing crop) under specific climatic conditions (Dimitriadou & Nikolakopoulos, 2021). RET is used as a standard for comparing the water demand of different crops and vegetation types and is typically estimated using empirical equations based on meteorological variables (Dimitriadou & Nikolakopoulos, 2021).

2.4.3 Factors that influence ET

Evapotranspiration (ET) is influenced by a wide range of factors that affect the availability of water at the land surface, the demand for water by vegetation and the atmospheric conditions that promote water loss from the land surface (Bastiaanssen et al., 2005; Zhang et al., 2022). Climatic factors such as temperature, humidity, solar radiation, wind speed and atmospheric pressure affect the rate of ET (Allen et al., 2011). Higher temperatures and lower humidity increase the rate of

ET, while lower temperatures and higher humidity reduce ET (Dimitriadou & Nikolakopoulos, 2021; Ochoa-Sánchez et al., 2019). Solar radiation and wind speed increase ET by providing energy for evaporation and transpiration and removing water vapour from the land surface (Valipour, 2017). Vegetation is another factor influencing ET. The type, density and health of vegetation affects the rate of transpiration and the overall water demand of the ecosystem (Deng et al., 2019; Qin et al., 2023). Vegetation with higher Leaf Area Index (LAI) and root density typically have higher water demands and higher rates of transpiration leading to higher overall ET rates (Dong et al., 2022; Jia & Wang, 2021). The availability of soil moisture is critical for sustaining ET rates (Phiri et al., 2013). Soil moisture influences the rate of evaporation from the soil surface and the amount of water available for transpiration by vegetation (Kirkham, 2023). Drier soils limit the rate of transpiration and overall ET rates (Kirkham, 2023). Geographical factors like slope, aspect and elevation also impact ET. These factors affect the distribution of solar radiation and wind speed and can create microclimates that influence ET rates (Bastiaanssen et al., 2005; Bennie et al., 2008; Fan et al., 2020). Areas with steeper slopes or higher elevations may experience lower temperatures and higher wind speeds leading to higher rates of ET (Allen et al., 2011) and the latter is true. Human activities such as land use change, deforestation and urbanisation can alter the distribution and density of vegetation, soil moisture and microclimatic conditions (Carlson & Arthur, 2000; Schirpke et al., 2023).

The interactions between these factors are complex and can vary depending on the specific ecosystem and climatic conditions (Yang et al., 2021). In arid regions with low soil moisture availability, the impact of vegetation density and soil moisture is more significant than in wetter regions with higher soil moisture availability (Greiser et al., 2024; Wang et al., 2012). A better understanding of these factors and their interactions is critical for developing sustainable water resource management strategies in different ecosystems and regions (Bhatt & Hossain, 2019; Raza et al., 2023).

2.4.4 Methods of Measuring/Estimating ET

There are several methods for measuring or estimating ET that vary in accuracy, complexity and cost (Ghiat et al., 2021). The choice of method depends on research questions, available resources

and the specific characteristics of the ecosystem being studied (Allen et al., 2011; Ghiat et al., 2021). Some of the most common direct methods for measuring AET are as follows:

i. Lysimeter, it's a large container that is placed in the ground and filled with soil to a specified depth (Howell, 2005). The lysimeter is then equipped with sensors to measure soil moisture, temperature and other environmental variables (Howell, 2005). The change in water content of the lysimeter over time is used to calculate ET rates (Huntington, 2010). Lysimeters are considered one of the most accurate methods for measuring ET but they are also the most expensive and require extensive maintenance (Ünlü et al., 2010);

ii. Eddy Covariance (EC), also referred to as the turbulent flux method, is a technique employed in micrometeorology to assess greenhouse gas (GHG) fluxes including water vapour, carbon dioxide and methane (Zawilski, 2020). By utilising high-frequency measurements of wind velocity, temperature and water vapour concentration, EC measures the exchange of heat and water vapour between the land surface and the atmosphere (Huntington, 2010). This method provides continuous, high-resolution measurements of ET but it requires specialised equipment and expertise (Phiri et al., 2013);

iii. Sap Flow technique is another method that directly measures the flow of sap within plant stems (Dodd et al., 2023; Forster, 2021). Sap flow measurements can be used to estimate plant level transpiration rates and contribute to understanding overall ET (Dodd et al., 2023; Forster, 2021). It's particularly useful for when investigating water use in trees and woody plants (Giménez et al., 2013); and

iv. The Scintillometer measures the turbulence caused by refractive index fluctuations in the atmosphere which can be related to the transfer of heat and moisture between the surface and the atmosphere (De-Bruin & Wang, 2017; Poisson et al., 2017). By analysing the fluctuations in light intensity over a known path length, the scintillometer provides estimates of surface fluxes, including ET (Poisson et al., 2017). It's particularly useful for studying ET over heterogeneous landscapes like agricultural fields or urban areas (Ward, 2017).

Each method has its advantages and disadvantages (Douna et al., 2021; Nader et al., 2000; Phiri et al., 2013). Combining multiple methods can help to increase the accuracy and reliability of ET measurements (Douna et al., 2021; Ghiat et al., 2021). Empirical methods (indirect) are another category of methods for estimating ET (Courault et al., 2005). These methods use empirical equations that relate ET to environmental variables (Srdić et al., 2023). The advantage of empirical methods is their simplicity and ease of use but they may be less accurate than direct methods and require calibration and validation against field measurements (Poyen et al., 2016). The following are some examples of empirical methods:

i. The water balance method estimates ET by accounting for the input and output of water from a defined area (Göltenboth & Erdelen, 2006). Inputs include precipitation and irrigation, while outputs include runoff, drainage and ET (Shamboko et al., 2012). The water balance method is simple and requires only basic monitoring equipments but it can be affected by errors in measurement or assumptions about water balance components (Göltenboth & Erdelen, 2006; Zhou et al., 2018). The equation is expressed as follows:

$$P + I = ET + Q + \triangle S + \triangle W + \triangle G \qquad \text{Eq. 1}$$

Comprising precipitation (P), inflow (I), evapotranspiration (ET), outflow (Q), along with variations in soil water content (ΔS), groundwater storage (ΔG) and surface water storage (ΔW) (Mohajerani et al., 2021);

ii. The Bowen ratio method measures the ratio of sensible heat flux (heat transfer due to temperature differences) to latent heat flux (heat transfer due to ET) using sensors that measure temperature and humidity (Zimba et al., 2022b; Spittlehouse and Black, 1980; Bowen, 2026). The Bowen ratio method is relatively simple and inexpensive but it requires steady-state conditions and can be affected by the quality of the sensors used (Everson et al., 2013; Zimba et al., 2022b). The equation is a follow:

$$\lambda E = \frac{\mathrm{R_n} - \mathrm{G}}{1 - \beta} \qquad \text{Eq. 2}$$

λE represents PET, R_n refers to net radiation, G signifies soil heat flux and β stands for the Bowen ratio (Buttar et al., 2018).

The equation for β being:

$$\beta = \gamma \frac{\triangle T}{\triangle e} \quad \text{Eq. 3}$$

γ denotes the psychometric constant (At sea level, where the atmospheric pressure is approximately 101.3 kPa, it is approximately 0.066 kPa/°C), ΔT indicates temperature variation and Δe represents the change in vapour pressure (Buttar et al., 2018); and

iii. The Penman-Monteith (PM) equation is a widely used empirical method (Allen, 2005). The equation combines the energy balance and aerodynamic methods to estimate the ET rate (Hao et al., 2018). The equation is as follow:

$$\lambda ET_{\mathrm{o}} = \frac{\triangle (R_{\mathrm{n}} - G) + \frac{86{,}400\ \rho_{\mathrm{a}} \mathrm{C_p} (e_{\mathrm{s}}^{\circ} - e_{\mathrm{a}})}{r_{\mathrm{av}}}}{\triangle + \gamma \left(1 + \frac{\mathrm{r_s}}{\mathrm{r_{av}}} \right)} \quad \text{Eq. 4}$$

γ denotes the psychometric constant, R_n refers to net radiation, G signifies soil heat flux, ρ_a air density in kg m^{-3}, C_p the specific heat of dry air (1.013 x 10^{-3} MJ kg^{-1} $^oC^{-1}$), e_s° the mean saturated vapour pressure in kPa computed as the mean e° at the daily minimum and maximum air temperature in ºC, r_{av} bulk surface aerodynamic resistance for water vapour in s m^{-1}, e_a the mean daily ambient vapour pressure in kPa, r_s the canopy surface resistance in s m^{-1} (Howell & Evett, 2004).

There several other empirical equations like the Priestley-Taylor (PT), Hargreaves-Samani method, Blaney-Criddle method and Turc method (Poyen et al., 2016). Empirical methods are useful in areas where field measurements or complex methods are not feasible or practical (Pinos, 2022). However, the accuracy of empirical methods depends on the quality of input data (Dong et al., 2024; Srdić et al., 2023).

2.4.5 Use of Empirical Equations for ET estimation in Africa

In Africa, scholars have emphasised the significance of ET in maintaining water resources, especially in the Okavango Delta in Botswana and the Nile Basin in Ethiopia (Moses & Hambira, 2018; Nooni et al., 2019). Similarly, in Zambia, researchers have conducted studies on the impact of ET on crop yields, water resources management and climate change. A study by Sharma (1988) evaluated the performance of some empirical methods: Penman (1948), Thornthwaite (1948), Morton (1983) and the water balance method in the Chambeshi River Basin and KRB, finding that each method was favourable to a particular condition. Additionally, JICA & MEWD (1995) investigated ET over the country using the Pan-evaporation method and Turc's formula, finding that Zambia is in a hydrological condition of precipitation deficit, amounting -100 mm $year^{-1}$ to -1100 mm $year^{-1}$ compared with PET. AET ranged from 65% to 95% of precipitation, highlighting its importance in managing water resources in the region (JICA & MEWD, 1995).

2.4.6 Estimating ET with RS

Remote Sensing (RS) models typically involve empirical equations but they can also incorporate physical principles and algorithms to relate remotely sensed data to ET estimates (Liou & Kar, 2014; Zhou et al., 2022). These algorithms are based on the energy balance principles which use remotely sensed data on surface temperature, vegetation cover and meteorological conditions (Allen et al., 2011; Bastiaanssen et al., 2005). These methods are useful for large-scale assessments of ET (Douna et al., 2021; Schowengerdt, 2007). Various models have been devised. Norman et al. (1995) proposed the two-source model of surface energy balance calculation (TSEB), while Bastiaanssen et al. (1998) introduced the Surface Energy Balance Algorithm for Land (SEBAL) as a one-source energy balance model. Su (2002) developed the Surface Energy Balance System (SEBS) and Allen et al. (2007) formulated the Mapping Evapotranspiration at high Resolution with Internalised Calibration (METRIC). Additionally, ETlook which is incorporated into the Water Productivity Open-access portal (WaPOR) database serves as another significant model in this domain (Blatchford et al., 2020; FAO, 2020).

2.4.7 Steps involved in using RS to estimate ET

To estimate ET using RS involves several steps. Some of the steps involved are as follows:

i. Obtain satellite imagery. RS based ET estimations require satellite or aerial imagery (multispectral images) with sufficient spatial and temporal resolution (Estes et al., 2001). The imagery should cover the study area and be acquired during periods of clear sky to minimise atmospheric interference (Phiri et al., 2013);

ii. Calculate vegetation indices. Vegetation indices such as the Normalised Difference Vegetation Index (NDVI) or the Enhanced Vegetation Index (EVI) are commonly used to estimate vegetation cover and activity (Schowengerdt, 2007). These indices are calculated using the reflectance values of the red and near-infrared bands from the satellite imagery (Douna et al., 2021);

iii. Estimate surface temperature. Surface temperature is a key component of the energy balance equation (Estes et al., 2001). It is estimated using thermal infrared bands from the satellite imagery or from Land Surface Temperature (LST) products derived from these bands (Douna et al., 2021);

iv. Compute energy balance components and ET. Energy balance components such as net radiation, soil heat flux and sensible heat flux are computed using satellite-derived surface temperature and vegetation indices, as well as meteorological data and ground-based measurements (Bastiaanssen et al., 2012). ET is computed from the energy balance equation which balances the incoming and outgoing energy fluxes at the land surface as residual of the equation derived from the latent heat flux (Zimba et al., 2022a); and

v. Validate ET estimates. RS based ET estimates are validated against ground-based measurements of ET such as Bowen ratio (Zimba et al., 2023), lysimeter (Howell, 2005) or eddy covariance (Zawilski, 2020) measurements. Validation is important to ensure the accuracy and reliability of the RS based ET estimates (Zimba et al., 2023).

2.4.8 Using RS for ET Estimation in Africa

Notably, Nsiah et al. (2021) estimated the spatial distribution of ET within the Pra River Basin of Ghana using Landsat 8 satellite images and SEBAL methodology. He reported a mean value of

5.63 mm day^{-1} for the spatial distribution of ET within the Pra River Basin, with high rates observed in water bodies and uncultivated forests, moderately average values for logged forests and low rates in settlements and bare landscapes (Nsiah et al., 2021). ET was higher in the upper western, central and eastern parts of the basin but lower in the northern part and some areas in the southern parts where settlement/bare landscape and logged forest dominate (Nsiah et al., 2021). Mohamed (2010) utilised SEBS for the Mkindo Basin, Tanzania. The study demonstrated good correlation between SEBS estimates and potential evaporation computed from climatological parameters with different land uses/cover types having different evaporative water use signatures (Mohamed, 2010). Dzikiti et al. (2019) evaluated the performance of the PM based MOD16 and the modified Priestley-Taylor (PT-JPL) models against measured ET datasets at three sites in South Africa with different ecosystems. The model performance of MOD16 and PT-JPL was observed to vary between sites and years, with the worst estimates occurring during years with prolonged mid-summer dry spells in the summer rainfall areas (Dzikiti et al., 2019). Studies in Zambia have been conducted in regions including the Luangwa River Basin and the Barotse Floodplain (Phiri et al., 2013; Zimba et al., 2022a), the use of RS to estimate ET in the KRB is scarce, if not non-existent. A study by Zimba et al. (2022a) focused on the use of open-source satellite evaporation models: WaPOR, Global Land Evaporation Amsterdam Model (GLEAM), Operational Simplified Surface Energy Balance (SSEBop), Moderate-resolution Imaging Spectrometer (MOD 16) and TerraClimate to assess the importance of phenology in the Miombo ecosystems of the Luangwa River Basin, Zambia. Another by Phiri et al. (2013) explored the use of the SEBS algorithm to estimate AET in the semi-arid Barotse Sub-Basin, Zambia. Similarly, Kabika et al. (2013) investigated the use of the SEBS to estimate AET in Sesheke, Zambia. The study calculated an average annual ET of 745 mm year^{-1}, which was compared to an annual precipitation of 765 mm year^{-1} (Kabika et al., 2013).

These studies highlight the potential of RS technology for estimating ET in Zambia, as well as the importance of considering local ecological factors and land use patterns when applying RS methods (Gibson et al., 2013; D. Phiri, 2019; TAB, 2013). The SEBAL model with a higher resolution of 30 metres as compared to others has been widely used and validated (Cheng et al., 2021) in similar landscapes such as Zambia. Hence deems more appropriate for the KRB.

2.4.9 Theorical background of the SEBAL model

The SEBAL model is a robust image processing algorithm designed to estimate the ET flux for individual pixels within a given raster image (Bastiaanssen et al., 2005). The model achieves this by solving the terms of the surface energy balance equation, utilising information from visible near-infrared (NIR) and thermal-infrared (IR) bands of the electromagnetic spectrum (Allen et al., 2011). The primary components of the surface energy balance equation are net radiation (Rn), sensible heat flux (H) and soil heat flux (G) (Bastiaanssen et al., 2005). The latent heat flux (LE), representing the energy associated with ET is then deduced as the residual in the equation (Allen et al., 2011; Bastiaanssen et al., 2005). The key equation expressing this relationship is:

$$\lambda ET = Rn - G - H \qquad \text{Eq. 5}$$

Here, λET is the latent heat flux, Rn is the net radiation flux at the surface, G is the soil heat flux and H is the sensible heat flux to the air (Bastiaanssen, 2000).

The computation of Rn involves estimating the algebraic difference between outgoing and incoming radiant energy fluxes. The equation for Rn is given by:

$$Rn = (1 - \alpha) \cdot RS\downarrow + RL\downarrow - RL\uparrow - (1 - \varepsilon 0) \cdot RL\downarrow \qquad \text{Eq. 6}$$

Where $RS\downarrow$ is incoming shortwave radiation, $RL\downarrow$ is incoming longwave radiation, $RL\uparrow$ is outgoing longwave radiation, $\varepsilon 0$ is surface thermal emissivity and α is surface albedo (Bastiaanssen, 2000).

The soil heat flux (G) is deduced using an empirical equation that considers land surface temperature (TS), albedo (α) and NDVI (Bastiaanssen, 2000). The equation for G is given by:

$$G = Rn \cdot \frac{TS}{\alpha} \cdot (0.0038\alpha + 0.0074\alpha^2) \cdot (1 - 0.98 \cdot NDVI^4) \qquad \text{Eq. 7}$$

Additionally, NDVI is calculated as the ratio of the differences in reflectivity for NIR and red bands to their sum (Bastiaanssen et al., 2005).

Furthermore, the sensible heat flux (H), representing heat loss to the air by convection and conduction (Bastiaanssen et al., 2005; Waters et al., 2002), is computed using the equation:

$$H = \frac{p.Cp.\Delta T}{rah} \qquad \text{Eq. 8}$$

Here, ρ is the density of air, Cp is the specific heat capacity of air, ΔT is the near-surface temperature difference and rah is the aerodynamic resistance to heat transport (Bastiaanssen, 2000).

2.4.10 Google Earth Engine

Google Earth Engine (GEE) is a powerful cloud-based geospatial analysis platform that enables users to analyse and visualize large-scale geospatial datasets (Gorelick et al., 2017). It offers a vast collection of satellite imagery and geospatial data, as well as a suite of tools for processing, analysing and visualising these data (Gorelick et al., 2017). The geeSEBAL app was developed by Laipelt et al. (2021) and incorporates the energy balance equation and its principles. The model has been developed and refined based on previous studies (Bastiaanssen et al., 2005; Waters et al., 2002) to ensure accuracy and reliability in estimating ET flux at the pixel level. Its user-friendly and ease to use.

2.5 Forest Inventory

Forest inventory is essential for understanding and managing forest resources, serving as a key aspect of the forest-water relationship (Dau & Mati, 2015; FAO et al., 2021). It refers to the process of collecting and analysing data on forest resources, such as the number, size, species and health of trees as well as other forest characteristics such as understory vegetation, soil properties and wildlife habitats (Köhl, 2004). Inventory data is used for a wide range of purposes including forest management, planning, research and policy development (Barrett & Fried, 2004; Köhl, 2004). Forest inventory typically involves a combination of field measurements and RS data (Wulder, 2004). Field measurements include the use of sample plots, transects and other sampling methods to collect data (Asrat & Tesffaye, 2013). RS data can also be used to estimate forest cover, biomass and other characteristics over large areas (Wulder, 2004).

One important aspect is the relationship between forest cover and ET (Komatsu & Kume, 2020). Forests are known to have higher ET rates than other land cover types and hence important in regulating the water balance (Mauser, 2021). RS based ET estimation models have emerged as powerful tools for estimating ET at regional to global scales (Estes et al., 2001). These models use satellite imagery and meteorological data to estimate ET and provide valuable information on the

spatial/temporal distribution and variability of ET (Estes et al., 2001; Schowengerdt, 2007). However, RS based ET estimation models require accurate information on the land cover type including forest cover in order to accurately it (Courault et al., 2005). This is where forest inventory data is handy. The data provides detailed information on forest characteristics, including species composition, age, structure and density (Asrat & Tesffaye, 2013; Barrett & Fried, 2004; Köhl, 2004; Wulder, 2004). By combining the two forest it is possible to identify areas of the landscape where forest cover is contributing significantly to the water balance and where forest conservation and management efforts may be most beneficial for sustaining water resources (Isaacson et al., 2023; Wan et al., 2021). Additionally, this information can be used to guide the development of more accurate and reliable ET estimation models, which can in turn inform more effective water resource management strategies (FAO et al., 2021; Fassnacht et al., 2024).

2.6 Forest-Water Nexus and ET in IBWT

InterBasin Water Transfer (IBWT) is a technique for enhancing water supply (Rollason et al., 2022). It involves moving excess water from a basin with an abundant supply to a basin with limited water resources (Gupta & van-der-Zaag, 2008). Prior to implementing IBWT assessments are conducted in both the donor and receiving basins to ensure the efficacy and sustainability of the transfer process (Abrishamchi & Tajrishy, 2005). There is no standard set of criteria for assessing IBWT, as current approaches are often prescriptive and subjective (Kibiiy & Ndambuki, 2015). Therefore, it remains important to adopt evaluation frameworks that considers IWRM principles (Gupta & van-der-Zaag, 2008; Roozbahani & Ghanian, 2024). This approach ensures that the transfer process is both sustainable and responsible, setting the stage for the pre-implementation assessments.

2.6.1 Pre-Implementation Assessment of Donor Basin

Assessment of the donor basin ensures a sustainable and efficient transfer process (Gupta & van-der-Zaag, 2008). The first step in this assessment is to evaluate the water availability and identify regions with surplus water (Dobbs et al., 2023). This involves analysing various factors such as precipitation patterns, river flow rates and reservoir capacities to establish the volume of excess water available for transfer (Dong et al., 2023). Environmental Impact Assessments (EIA) are critical, they entail a detailed study of the hydrological, ecological and socio-economic impacts of

reduced water availability in the donor basin (Joseph et al., 2019; Laval et al., 2020). It identifies potential risks to local fauna and flora as well as changes in land use patterns and community livelihoods (ECZ, 2010). The EIA aims to develop mitigation measures that minimize these adverse effects, ensuring that water transfer does not unduly harm the environment or disrupt local economies (ECZ, 2010). Concurrently, an infrastructure evaluation assesses the current state of the donor basin's water management infrastructure to determine its suitability for water transfer (Murgatroyd & Hall, 2020). This evaluation includes inspecting dams, canals, pipelines and other related structures to ensure they can handle the increased water flow without compromising safety or efficiency (Murgatroyd & Hall, 2020; Pittock et al., 2009). By integrating these assessments, IBWT projects can be designed and implemented with a comprehensive understanding of the donor basin's capabilities and limitations laying the groundwork for a successful water transfer initiative (Rollason et al., 2022).

2.6.2 Pre-Implementation Assessment of Receiving Basin

Water demand and deficit analysis is the starting point for determining the water requirements in the receiving basin (Kibiiy & Ndambuki, 2015; Tully & Young Inc, 2007). This involves examining population growth, industrial development and agricultural water use trends to project future water demands (JICA & MARD, 2003). By identifying areas already experiencing water stress, planners can prioritize water allocation and devise strategies to ensure a fair and effective distribution of transferred water (Kibiiy & Ndambuki, 2015). This analysis helps to align the water transfer plan with the actual needs of the basin and prevents over-extraction or under-supply (Roozbahani & Ghanian, 2024). Ecosystem and Land Cover Assessment (ELCA) examines the environmental impact on the receiving basin by analysing its vegetation, soil conditions and wildlife habitats to understand how increased water availability might influence these factors (Khand et al., 2021; Zhuang, 2016). Understanding the resilience and sensitivity of ecosystems helps in devising conservation strategies that reduce potential adverse effects (Gupta & van-der-Zaag, 2008; Khand et al., 2021). By identifying vulnerable areas, the planning team can develop measures to protect critical habitats, maintain biodiversity and prevent soil erosion or degradation that could arise from altered water flows (National Research Council, 2005). Stakeholder consultation is also an integral part of the IBWT planning process, ensuring that the perspectives and concerns of local communities in the receiving basin are taken into account (Lim et al., 2022;

National Research Council, 2005). Through consultations with stakeholders, including community leaders, indigenous groups and water user associations, planners gain valuable insights into the socio-economic priorities and preferences for water management (UN Water/Africa, 2007). These engagements help to build consensus, address community-specific needs and foster a sense of ownership over the IBWT project (Karadeniz & Arpa, 2022; UN Water/Africa, 2007). Incorporating stakeholder input can lead to a more inclusive approach, facilitating smoother implementation and long-term success of the water transfer initiative (Karadeniz & Arpa, 2022).

2.6.3 Evolution and Holistic Assessment of IBWT

IBWT has a long history, with the majority of schemes implemented in the early 1900s rising to a peak in the 1970s and 1980s (Gupta & van-der-Zaag, 2008). The surge of academic interest in the planning and delivery of projects in the 1980s, prompted by the large number of schemes developed during that time, explored a diverse range of topics spanning ecology, hydrology, economics and socio-cultural impacts (Ghassemi and White, 2007; Rollason et al 2022). Relatively little scholarship has explored IBWT schemes using a holistic perspective (Rollason et al., 2022). Previous project evaluations have focused on individual schemes or on narrow impact evaluations. Rollason et al. (2022) provides an analysis of IBWT schemes exploring their spatial and temporal distribution underlying drivers and the ongoing debate regarding their implementation. The study reviews the arguments for and against IBWT schemes and examines conceptual models used to assess their efficacy. According to Rollason et al. (2022), IBWT is gaining popularity as a supply-side solution to address water scarcity, with water managers increasingly viewing it as a key tool for future water resource management. However, Rollason et al. (2022) notes that current IBWT approaches often prioritize water-centric policies and practices without adequately considering social and environmental concerns. This imbalance can lead to unintended consequences such as negative impacts on local ecosystems, communities and broader environmental sustainability. To address these concerns Rollason et al. 2022 examined the Socio-Ecological Systems and Water-Energy-Food (WEF) Nexus models, exploring their applicability in assessing IBWT schemes. Despite their merits, neither model offers a comprehensive solution for balancing the various factors involved in IBWT projects. To bridge this gap, Rollason et al. (2022) proposes an enhanced WEF model (eWEF) designed to facilitate a more holistic approach to water management. The eWEF model aims to integrate social, environmental and economic considerations into the

planning and assessment of IBWT projects. By doing so, it provides a framework for more sustainable IBWT practices guiding water managers and decision-makers in creating mega-scale engineering interventions that align with broader water management strategies and ensure long-term sustainability.

The assessment and modelling of water loss due to ET from different land covers are crucial when considering IBWT (FAO, 2019). Liu et al. (2022) conducted a study that modified the Water Supply Stress Index (WaSSI) model to estimate mean water yield and determine the proportion of mean flow originating from forested lands. This research aimed to understand the role of forested lands in contributing to surface drinking water supply systems including basins receiving water via IBWT (Liu et al., 2022). The WaSSI hydrologic model was used to estimate water supply from various land cover types (Liu et al., 2022). In this model, precipitation was divided into rain and snow based on air temperature with a conceptual approach to snow accumulation and melt (Caldwell et al., 2019). The soil profile was separated into an upper thin layer and a much thicker lower layer, supplying moisture to meet ET demands (Caldwell et al., 2019). The model calculates monthly ET as a function of PET, precipitation and Leaf Area Index (LAI) incorporating empirical relationships derived from multisite EC measurements (Sun et al., 2011). Water yield for each land cover type was calculated by summing surface runoff from pervious and impervious surfaces, interflow and base flow (Sun et al., 2011). These calculations accounted for losses due to changes in soil water storage, evaporation and transpiration from vegetation (Khand et al., 2021). Liu et al. (2022) found that forested lands generate almost half (46%) of the surface water supply and concluded that including IBWTs in hydrologic models is critical to accurately assess the contribution of forested river basins to surface drinking water supply. Omitting IBWTs could lead to an incomplete understanding of water resource dynamics, especially considering the impact of climate change and human population growth (Liu et al., 2022).We see here that, this model was modified and accounted for land cover/forest ET.

2.7 Summary

The KRB in Zambia grapples with water insecurity due to climate change, land-use changes and water abstraction (Hamududu & Ngoma, 2018; WWF, 2018). To address this, investigation of forest-water interactions focusing on ET is an important aspect (FAO, 2019; Mauser, 2021;

Mendicino & Senatore, 2012). RS techniques in combination with forest inventory facilitate this operation. Current research has not sufficiently explored the impact of forests on water loss through ET particularly from various tree species and woodlands (Creed & Noordwijk, 2018; FAO, 2019; Mauser, 2021) in the KRB. Given the importance of IBWT in managing water resources, this knowledge gap could significantly affect planning and management strategies. Implementing IBWT would require an understanding of the forest-water nexus, highlighting the need for pre-implementation assessments that consider forest cover's role in water loss (Liu et al., 2022). Identifying forest species and types with high ET rates is essential to account for these factors during IBWT planning. This approach ensures a balance between forest conservation and IWRM (Liu et al., 2022; Rollason et al., 2022). RS is the suitable method for estimating ET due to the large spatial extent of the study area and the complexity of the forest-water system. The easiness and user friendly of geeSEBAL facilitates this operation. RS based estimation of ET in this case, provides frequent measurements of ET which are useful for identifying patterns and trends in ET (Zimba et al., 2022a). In addition, RS in combination with other methods (such as ground-based measurements) improves accuracy and validation of ET estimates (Glenn et al., 2007). However, it is important to acknowledge the limitations and uncertainties associated with remote sensing-based ET estimates and to carefully evaluate the quality and suitability of RS data for the specific study area and research question (Glenn et al., 2007; Samboko, 2016; Zimba et al., 2022a). Overall, the relevance of land cover/forest ET can be shown with a water balance description, including the interbasin water transfer.

CHAPTER THREE: DESCRIPTION OF THE STUDY AREA

3.1 General Remarks

This chapter describes the location, climate, physical, socio-economic characteristics and research efforts of the study area.

3.2 Location

The Upper Kafue River Sub-Basin (UKRSB) is found in Zambia within the main Kafue River Basin (KRB) (Figure 3.1). The Kafue River originates close to the border between Zambia and Congo in North-Western Province of Zambia and flows southwards to join the Zambezi River (Simfukwe, 2014). It is a geographically and ecologically significant region in Zambia, covering the entire Copperbelt Province, partly the Central and Northwest provinces (WWF, 2016).

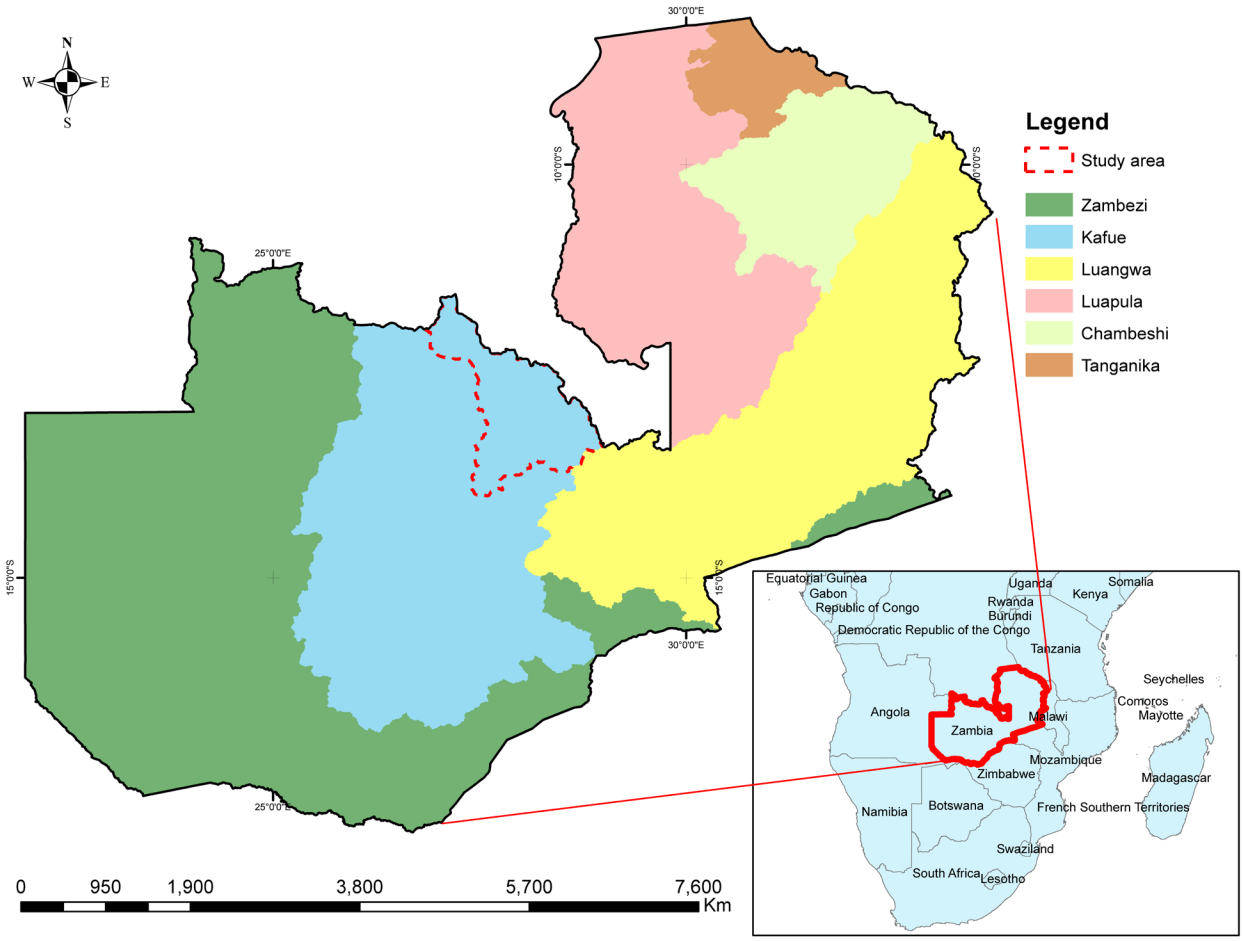

Figure 3.1: Map of Zambia in the Southern part of Africa with six main river basins in Zambia, highlighting the UKRSB study location (Lehner et al., 2008).

It extends between 29°0'0"E and 26°35'0"E longitudes and 14°0'0"S and 11°35'0"S latitudes (Figure 3.2) spanning an area of 24,820.23 km² with a river discharge rate of 154.29 m³/s at Machiya (WARMA, 2021). Vegetation types are noticed in Figure 3.2, highlighting a stream order of the Kafue River and its tributaries. It indicates the main sampling points within each woodland research was conducted: Kalahari Woodland; Munga Woodland; Miombo/Chipya Woodland; and Parinari Woodland.

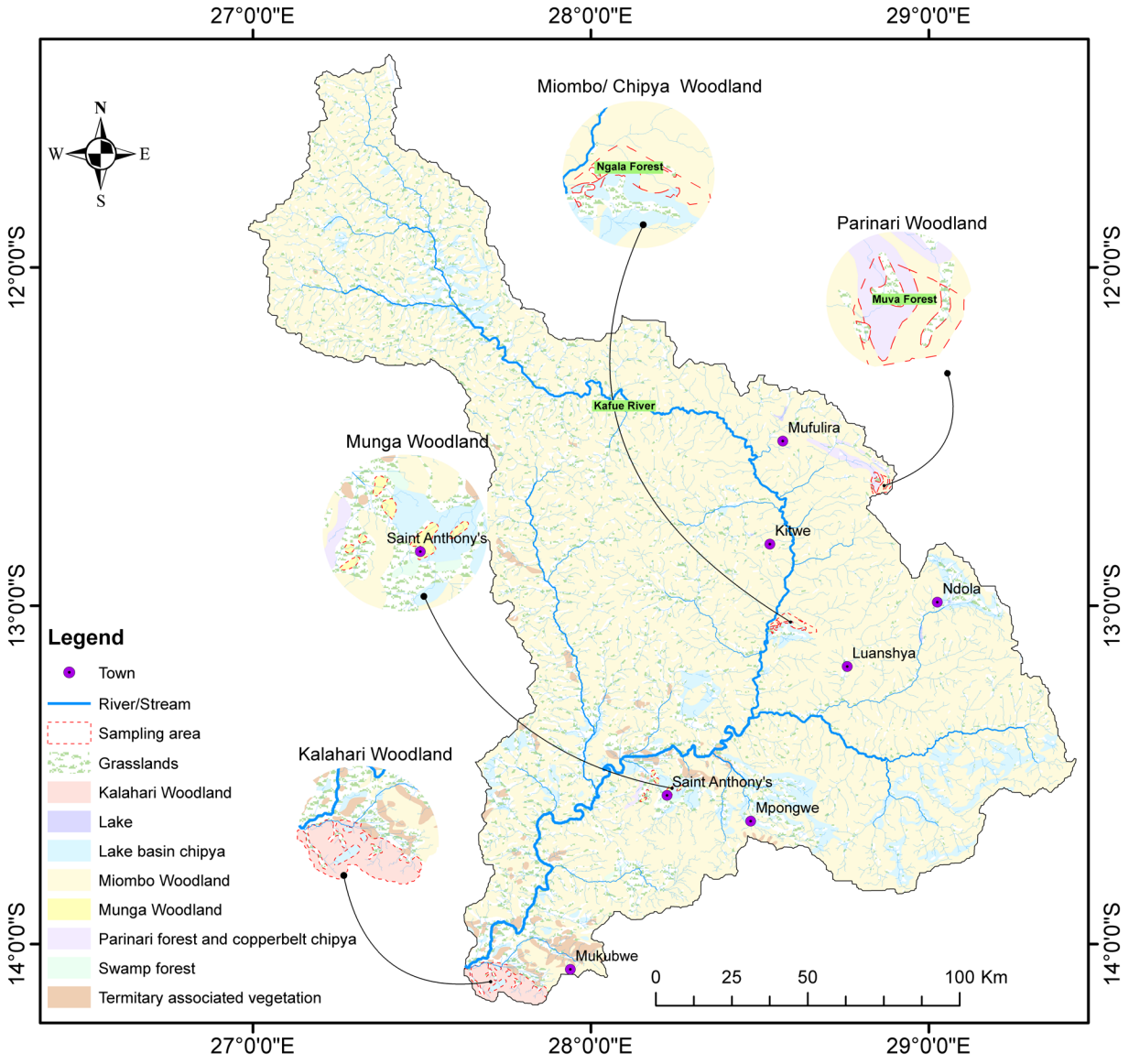

Figure 3.2: Map of forest types in the UKRSB spanning North-Western, Central and Copperbelt provinces of Zambia adapted from Chidumayo (2016), with sampling locations highlighted and a superimposed river network of the Kafue River and its tributaries.

3.3 Climate

Zambia experiences humid subtropical climatic conditions, characterised by hot humid summers and mild to cool winters with moderate seasonality (Lweendo et al., 2017). Precipitation in Zambia is derived mainly by the Inter Tropical Convergence Zone (ITCZ) and El Niño Southern Oscillation (Chisanga et al., 2023). The average yearly rainfall and number of rainy days vary between 657 mm $year^{-1}$ and 68 days to 1402 mm $year^{-1}$ and 142 days (Brigadier et al., 2016; Lweendo et al., 2017). With high intra-seasonal variations, precipitation decreases from north to south, showcasing spatial variability (Lweendo et al., 2017). Two distinct seasons are experienced, the rainy season (November to April) and dry season which is subdivided into dry-cold season (May to August) and dry-hot season (September to October) (Mwelwa, 2004). The average annual temperature and rainfall in the UKRSB are 20.9°C and 1048.8 mm $year^{-1}$ respectively with projected reductions in rainfall anticipated coupled with an increase in temperature (Hamududu & Ngoma, 2018; Lweendo et al., 2017).

3.4 Geographical and Physical Characteristics

Characterised by a smooth plateau with subdued slopes, scattered inselbergs and shallow, wide drainage patterns, the UKRSB exhibits its distinct features (Lweendo et al., 2017; Mwelwa, 2004). The slope gradient ranges from 1:1000, whereas the elevation ranges from 1000 to 1570 m above sea level (Figure 3.3a) with the highest elevation being in the north and gradually decreasing towards the south (Lweendo et al., 2017; RCMRD, 2015). Comprising a 65% crystalline and meta-sedimentary Basement Complex, the UKRSB's geotectonic profile has undergone chemical weathering to produce saprolite rock, with thickness ranging from 25 to 60 meters (Mwelwa, 2004). The hydrology of the UKRSB is significantly impacted by this rock formation, which encompasses a Basement Complex, Muva-Conglomerate, small areas of Alluvium and Kalahari sands and Kundelungu Limestone (Figure 3.3b) (Lweendo et al., 2017; Mwelwa, 2004). The vegetation type is diverse with four primary ones, Miombo Woodland, Munga Woodland, Kalahari Woodland and Parinari Woodland (Figure 3.3c) (Lweendo et al., 2017). Of these, the Miombo Woodland dominates the forest area, accounting for 80% and is characterised by *Isoberlinia*, *Brachystegia* and *Julbernardia* species (Chidumayo, 2016; Lweendo et al., 2017). The UKRSB also boasts a diverse array of soil types (Figure 3.3d), each with its own unique characteristics that contribute to the ecological and agricultural systems of the region (Chidumayo, 2016). Among the

most prominent of these soil types are acrisols, ferralsols, greysols, leptosols, regosols and vertisols (Figure 3.3d) (USDA, 2022).

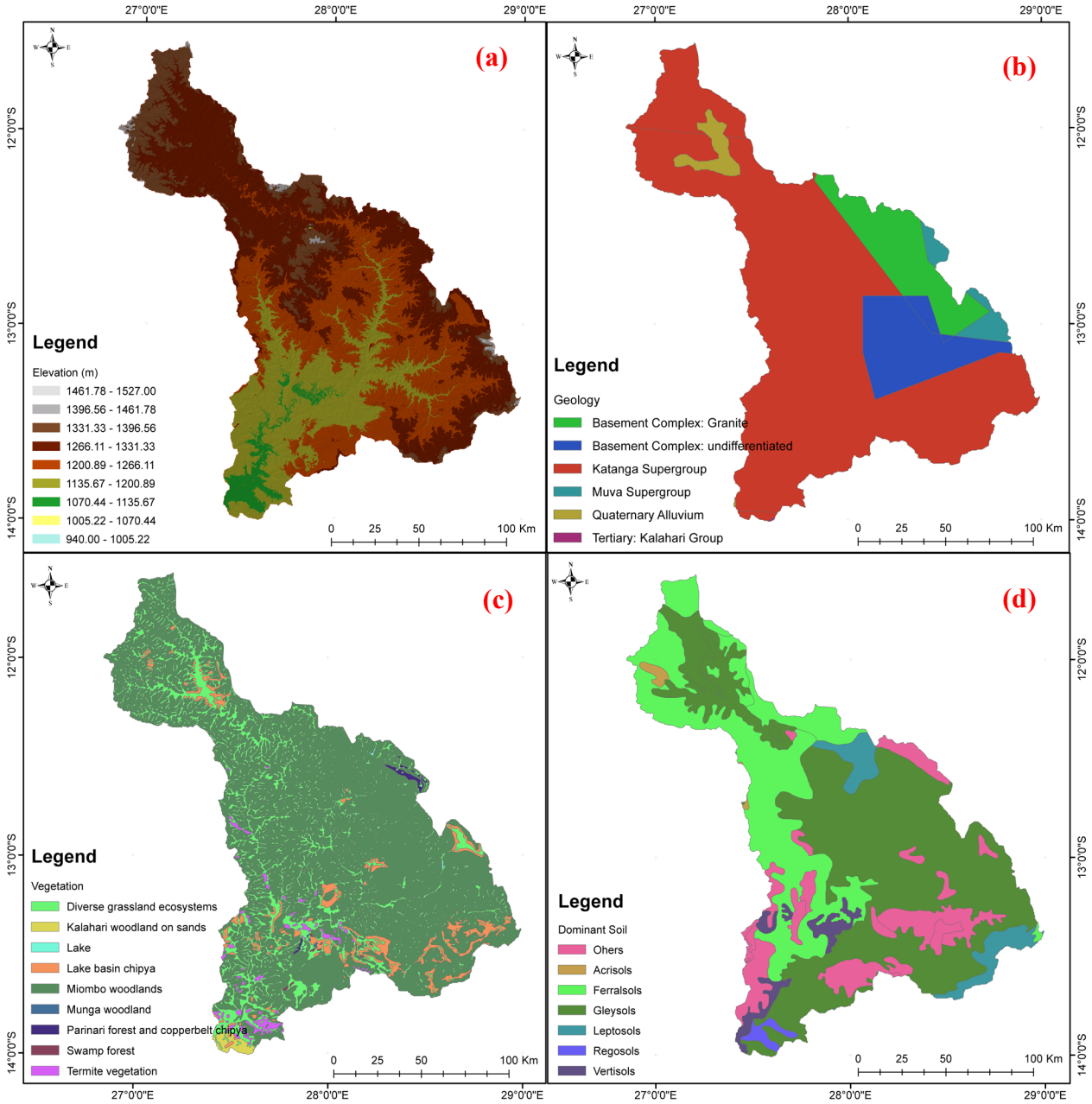

Figure 3.3: Composite image displaying four thematic maps of the UKRSB, Zambia. (a) 30 metre resolution Digital Elevation Model Map (RCMRD, 2015); (b) Geology Map (Persits et al., 2002); (c) Forest Types Map (Chidumayo, 2016); and Soil Types Map (USDA, 2022).

3.5 Demographics and Socioeconomic Characteristics

The UKRSB is home to a growing population estimated at 3 million people, with a projected annual growth rate of 2.5% (ZamStats, 2022). The population is mainly rural, with over 80% of the inhabitants living in rural areas (Sopitshi & Van, 2015). Urban populations are concentrated in the larger towns such as Kitwe, Ndola and Chingola, which are major centres of commerce and industry (Taylor, 2006). There over 20 ethnic groups, with Lamba being the largest ethnic group (Sopitshi & Van, 2015; Taylor, 2006).

The region is characterised by high poverty levels, with over 60% of the population living below the poverty line (UN, 2015; WBG, 2018; ZamStats, 2022). The lack of access to basic services such as water, health and education is a major challenge facing the people (IMF, 2002; UN, 2015; WBG, 2018). Water scarcity is a critical issue with recurrent droughts and erratic rainfall patterns (ACAPS, 2024; WWF, 2018). This situation has been compounded by the effects of climate change, leading to reduced agricultural productivity and food insecurity (Hamududu & Ngoma, 2018; WWF, 2018).

Land use and cover is largely influenced by the impacts of the mining industry, its related industrial and urban activities, such as copper, cobalt and emerald mining (Denga et al., 2023; Kalaba, Quinn, Dougill, et al., 2013). This has led to changes in land use and cover, with industrial plantations of Eucalyptus and Pines replacing Miombo woodlands (Chileshe, 2001; Chungu et al., 2010a). These plantations have been established for commercial purposes, mainly for the production of pulp & paper, timber and transmission poles (Chungu et al., 2010b). The growing demand for energy and timber has also led to an increase in illegal logging, further exacerbating deforestation (Vinya et al., 2011). Apart from mining, the region's economy is also driven by manufacturing, farming, livestock rearing and tourism (Phiri et al., 2020). Small-scale subsistence farming is the mainstay of the rural economy, with maize, cassava and groundnuts being the major crops grown (Denga et al., 2023; Phiri et al., 2020). Livestock production, mainly cattle, goats and sheep are also prevalent (Denga et al., 2023; Phiri et al., 2020). The predominant Miombo woodlands, provide timber for construction, fuelwood and non-timber forest products such as mushrooms, fruits and medicinal plants (Chidumayo, 2016; Vinya et al., 2011).

3.6 Research and Conservation Efforts

The UKRSB is home to endangered plant and animal species, has it also been a vital resource for the human population (WWF, 2018). As such, a number of research and conservation efforts have been undertaken in recent years. Another important area of research in the UKRSB is the impact of climate change on the region's natural resources (Hamududu & Ngoma, 2018). As with many other regions in Africa, the UKRSB is highly vulnerable to the effects of climate change, including increased temperatures, altered precipitation patterns and more frequent extreme weather events (Hamududu & Ngoma, 2018). Efforts to research and conserve the natural resources, promoting of sustainable water use and management practices have been prevalent (WWF, 2018). Research in this area has focused on the impact of mining and other industrial activities on basin's water quality and quantity (Kambole, 2003). The mining industry is known to have significant impacts on water resources including pollution from waste and run-off, as well as depletion of groundwater reserves (Kříbek et al., 2014; Lindahl, 2014; River & Pettersson, 2002; WWF, 2018). Other initiatives include rainwater harvesting, water conservation education and the development of community-based water management plans (WBG, 2018). Researchers have been studying the effectiveness of various water management strategies, such as wetland restoration, erosion control and improved irrigation practices (WWF, 2018). These efforts have been aimed at protecting the basin's aquatic ecosystems and species (WWF, 2016; 2018). More recently, the ORTARChI project 2022 in Zambia, focusing on water conservation has been conducting research on the feasibility of IBWT (Lusaka Times, 2022), demonstrating the growing interest in exploring sustainable water management solutions. This study is part of this large ORTARChI Project whose thematic area is Water conservation: Enhancing catchment protection and management in Upper Zambezi and Luapula River basins.

CHAPTER FOUR: METHODOLOGY

4.1 Overview

This chapter outlines the methods employed to achieve the three specific objectives, highlighting sampling procedures and outlining the data analysis methods of both primary and secondary data.

4.2. Research approach and design

The study adopted a mixed-methods approach, integrating both qualitative and quantitative methods (Creswell & Clark, 2017). The research was structured using a sequential explanatory design, where quantitative remote sensing and field-based data collection were complemented by qualitative assessments, including systematic literature reviews (Webster & Watson, 2002) and indirect observations (CDC, 2018; Taylor-Powell & Steele, 1996).

The research design is visually represented in Figure 4.1, illustrating the sequential data flow from data collection to analysis and synthesis.

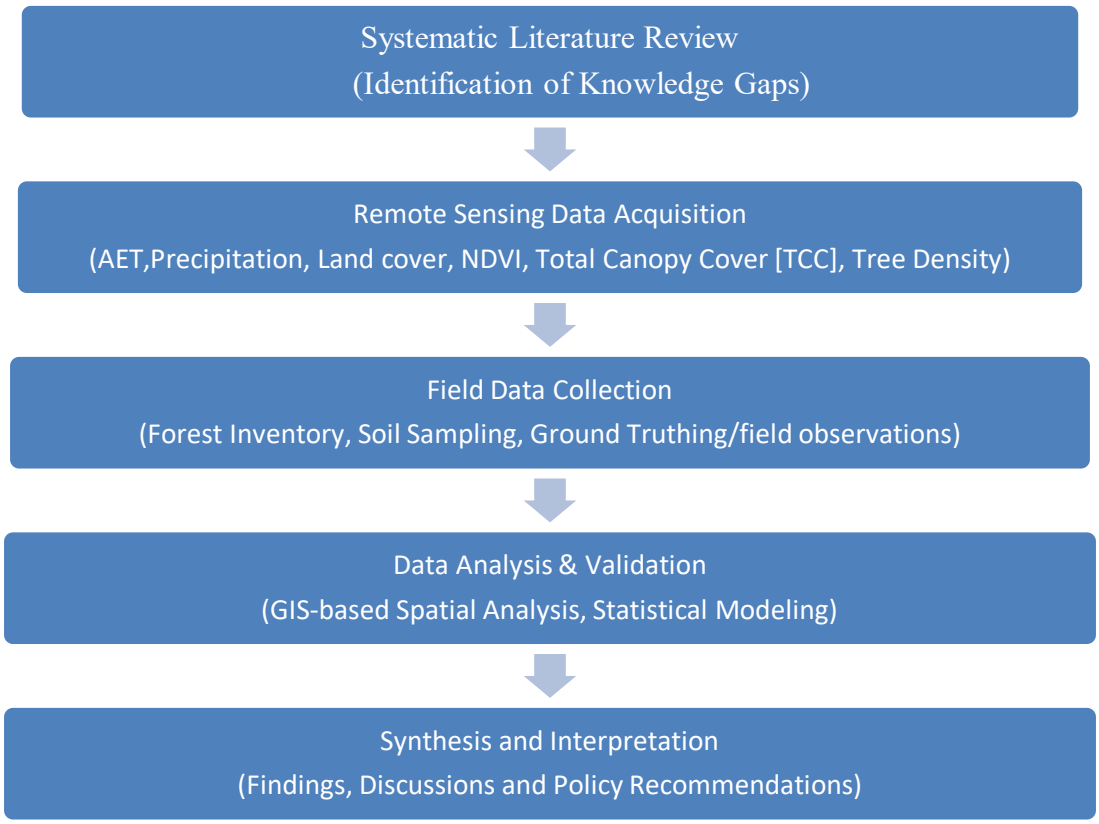

Figure 4.1: Diagrammatic research design.

4.2.1 Explanation of the Research Design

The process begins with a systematic literature review (Webster & Watson, 2002) to provide foundational knowledge, followed by the collection of remote sensing data (Lillesand et al., 2015) and in-field measurements. These datasets are then analysed and validated through a combination of GIS, statistical techniques and bibliometric methods (van Eck & Waltman, 2010). Finally, the findings are synthesized to draw actionable insights. This multi-step design facilitates an evaluation of the hydrological responses to different land covers.

4.3 Target Area

The UKRSB was the target area as indicated in chapter 3 of this dissertation. Forest inventory and field observation were done in the Kalahari, Munga, Miombo/Chipya (Ngala forest) and Parinari (Muva forest) woodlands as highlighted in chapter 3 figure 3.2. This included pine and eucalyptus plantations in the Miombo woodlands.

4.4 Sampling

The following describe the sampling procedures. Objective one and had no sampling procedure as its process does not involve sampling.

4.4.1 Sampling Design and Strategy

A purposive stratified sampling approach was employed to ensure representativeness of different woodland types (Patton, 2015).

4.4.2 Selection Criteria

The study area was divided into four primary woodland categories as described in subsection 4.3. Sampling sites were further selected based on AET rates of individual pixels of the spatial distribution AET in each woodland and land cover (primely forest cover). Five pixels with high AET rate in each woodland were picked. Field visits confirmed the accuracy of remotely sensed classifications, ensuring that sample plots represented distinct land cover categories (Lu & Weng, 2007).

4.4.3 Field Sampling Techniques

Sampling involved nested plots within 30m x 30m grid cells, following standard forest inventory: Tree Diameter at Breast Height (DBH) – Measured using a diameter tape (Kangas & Maltamo, 2006). Tree height – estimated with a clinometer (Asrat & Tesffaye, 2013; Kangas & Maltamo, 2006; Köhl, 2004). Tree species identification – conducted using field guides, local expert knowledge and know your trees book guide by Storrs (1995). Canopy cover estimation – measured using crown radius methods and canopy closure estimates (Asrat & Tesffaye, 2013. Soil sampling – five evenly distributed 10 cm depth soil samples were collected per plot for particle size analysis (Kangas & Maltamo, 2006).

4.5 Data Collection

The study employed a multi-source data collection strategy integrating systematic literature review (Webster & Watson, 2002), remote sensing (Lillesand et al., 2015) and field-based data collections (FAO, 2019).

4.5.1 Objective 1 Methodology: Systematic Literature Review

Google Scholar, being one of the largest search engines globally (Gusenbauer, 2019) was utilised to conduct a systematic search covering the period from 1970 to 2023. PRISMA guidelines (Appendix 1) were used to establish a review protocol which involved data identification and data cleaning (Linnenluecke et al., 2020; Moher et al., 2009). A search was executed using strings: "forest water" Zambia, "Forest-water nexus," and "Kafue River Basin" as data retravel strategy. This approach ensured the retrieval of relevant reports, conferences and peer-reviewed journal articles from a diverse range of sources (Donthu et al., 2021). All identified papers were exported as Research Information Systems (RIS) format and stored in a single folder for analysis (Bukar et al., 2023; van-Eck & Waltman, 2019). Titles and abstracts were reviewed to determine the paper's eligibility to be included in the study (Page et al., 2021). Papers that did not fall in the subject category were removed, no full text articles, duplicates and articles not in English (Page et al., 2021). After the application of the exclusion criteria, narrowed down to a total of 25 papers more relevant to the study.

4.5.2 Objective 2 Methodology: Remote Sensing Data Acquisition

A variety of remote sensing datasets were acquired and processed. These datasets include AET, Normalized Difference Vegetation Index (NDVI), Tree Total Canopy Cover (TCC) and Tree density. The following sections detail the methodologies used for acquiring and processing these datasets.

4.5.2.1 Actual Evapotranspiration (AET)

Evapotranspiration (ET) data was collected using the web application geeSEBAL, an application developed by Laipelt et al. (2021) employing the SEBAL algorithm through Google Earth Engine (GEE), accessible at the link: https://etbrasil.users.earthengine.app/view/geesebal. Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images, together with Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) images were processed spanning from 1st January, 2009 to 31st December, 2022 with a cloud cover constraint of 0% to 30%. These images, each covering an area of 55 km x 55 km, were mosaicked using QGIS desktop version 3.28.2 and subsequently clipped to the UKRSB to facilitate focused analysis. A linear interpolation method was applied to generate missing data value and annual ET rates (Anderson & Gough, 2018; Noor et al., 2014). To which the general equation appears as follows:

$$y = y_1 + \frac{(x - x_1).(y_2 - y_1)}{(x_2 - x_1)} \qquad \text{Eq. 9}$$

Where, $(y_2 - y_1)$ are coordinates of the first known point, $(x - x_1)$ are the coordinates of the second known point, x is the given x-value for which you're estimating y, y is the interpolated y-value at x (Bayen & Siauw, 2015).

To augment the understanding of the hydrological cycle, precipitation data was obtained from the WaPOR web app version 2.1, which can be accessed via the link: https://data.apps.fao.org/wapor whose source is from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset (FAO, 2020). In addition to ET and precipitation data, land cover information was obtained to contextualise the analyses. A land cover map at 10m resolution was acquired from the Environmental Systems Research Institute (ESRI) ArcMap, a GIS mapping web-based software, which can be accessed via https://livingatlas.arcgis.com/landcoverexplorer (Karra et al., 2021).

The maps are generated using Impact Observatory's deep learning AI land classification model, applied to the Sentinel-2 Level-2A image collection on Microsoft's Planetary Computer (Karra et al., 2021).

After obtaining the spatial distribution raster file for the annual distribution rate of ET for the year 2022, each type of woodland was isolated and the attribute table for each woodland was extracted using QGIS desktop version 3.28.2. This attribute table contained pertinent information on the annual ET rate for each 30m x 30m pixel within the woodland areas. Subsequently, the annual ET rate table was sorted in descending order to identify the highest values enabling the highlighting of corresponding pixels on the screen interface. Following this, a visual validation process was conducted wherein pixels with high ET values were scrutinised against a google satellite base layer map in QGIS. This visual inspection ensured that only forest or vegetation and not water bodies were present in those pixels, thereby ensuring the accuracy of the subsequent analyses. With verified high ET value pixels in hand, the next step was to establish sample plots for further investigation. Five pixels in each woodland were selected based on their high ET rates and confirmed vegetation cover. Utilising QGIS tools, the coordinates of each pixel's vertices were extracted and recorded (Figure 4.2). These coordinates were then transferred onto a Garmin GPSMAP 62s device for navigation purposes, facilitating the establishment of 30m x 30m sample plots at each designated location.

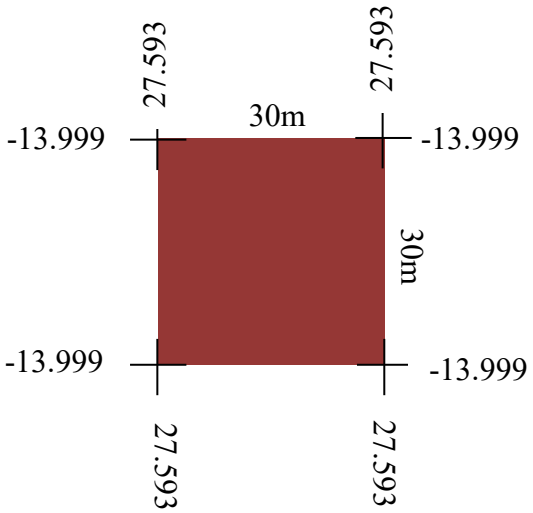

Figure 4.2: Illustration of a pixel sample design, extracting pixel vertex coordinates for the sample plots for the UKRSB, Zambia.

4.5.2.2 Normalized Difference Vegetation Index (NDVI)

To analyse the correlation between NDVI and AET, NDVI data was collected using Sentinel-2 imagery. The NDVI data collection was focused on the year 2022, from 1st January to 31st December. Sentinel-2 imagery was selected based on cloud cover less than 10% to ensure high-quality data. The Red (Band 4) and Near-Infrared (NIR) (Band 8) bands were used for NDVI calculation. A script (Appendix 3) was implemented in GEE to calculate NDVI for the specified period and area. Using QGIS desktop version 3.28.2, the NDVI images were projected to the WGS 1984 UTM Zone 35S (EPSG 32735) projection to match the AET data. This ensured that both datasets were in the same coordinate system and projection. The cell size for NDVI and AET images was standardized, and images were aligned to ensure consistency in spatial resolution and extent. A fishnet grid was created to cover the entire study area. The fishnet was clipped to match the boundaries of the UKRSB study area. The fishnet grid was used to extract NDVI and AET values at each grid cell. This was done using the "Extract Multi Values to Points" tool in QGIS, which allows the extraction of raster values to the fishnet grid points. The attribute table containing the extracted NDVI and AET values was exported as an Excel file. This facilitated further statistical analysis, including the correlation analysis between NDVI and AET.

4.5.2.3 Total Canopy Cover (TCC) and Tree Density

Tree Total Canopy Cover (TCC) for the UKRSB study area was obtained from the canopy cover dataset developed by Hansen et al. (2013) at 30 meters resolution. This dataset is accessible through Global Forest Watch (www.globalforestwatch.org) and downloaded from https://glad.umd.edu/Potapov/TCC_2010/. The specific data file “treecover2010_10S_020E.tif” was downloaded. This file provides tree canopy cover data for the year 2010. The downloaded GeoTIFF file was imported into QGIS Desktop version 3.28.2. The study area, UKRSB, was defined as a polygon shapefile. The treecover2010_10S_020E.tif file was clipped to the boundaries of the UKRSB study area using the "Clip Raster by Mask Layer" tool in QGIS. This step ensured that only the relevant data for the study area was retained for analysis. All data files in QGIS were projected to WGS 1984 UTM Zone 35S (EPSG 32735).

Tree density data was sourced from the dataset created by Crowther et al. (2015). This dataset, accessible at https://figshare.com/articles/dataset/Global_map_of_tree_density/3179986 provided

a resolution of 0.9 kilometres. The raster data was first imported into QGIS Desktop version 3.28.2 and overlaid with a polygon shapefile defining the UKRSB study area. Using the "Clip Raster by Mask Layer" tool in QGIS, the dataset was constrained to the study area's boundaries to ensure relevance and accuracy in subsequent analyses. All data layers were projected to WGS 1984 UTM Zone 35S (EPSG 32735) to maintain consistency in spatial referencing and analysis procedures.

4.5.3 Objective 3 Methodology: Forest Inventory and field observations

The forest inventory (collected in September, 2022 and April, 2023) process involved fieldwork (Kangas & Maltamo, 2006) with support from the Forest Department under the Ministry of Green Economy and Environment of Zambia. A technical field officer from the Forest Department and a local guide from the neighbouring communities joined the inventory team. The local guide, identified as local botanist was familiar with the forest routes and species' local names, providing assistance in navigating the terrain (Figure 4.3a). To facilitate locomotion between different locations within the forest a motorcycle was used (Figure 4.3b). A Global Positioning System (GPS) device was used to locate the coordinates of each plot's vertices and GPS readings were taken at each point to ensure precise positioning. To ensure accuracy, the dimensions of each sample plot were verified using a 100 m measuring tape (Figure 4.3c) (Barrett & Fried, 2004; Köhl, 2004). Ground truthing surveys were also conducted to validate the presence of forest and absence of water bodies (Kangas & Maltamo, 2006; Phiri, 2019). Note-taking was used to document the observations and other important details, including species' local names and any unique characteristics (Figure 4.3d) (FAO, 2015).

Figure 4.3: Field data collection in the UKRSB (Mufulira, Luanshya, Mpongwe and Ngabwe), Zambia. (a) Navigating a thick forest terrain; (b) Using a motorcycle to move from point to another; (c) Marking sample plot; and (d) Note taking.

Data collection effort encompassed various parameters. The sampling procedure involved the following:

i. Tree diameter (DBH) was measured using a diameter tape (Figure 4.4a) (Kangas & Maltamo, 2006);

ii. Tree height was estimated using a clinometer (Figure 4.4b) (Asrat & Tesffaye, 2013; Kangas & Maltamo, 2006; Köhl, 2004);

iii. Tree species were identified using the Know your trees guide book by Storrs (1995) and also with help of a local guide by identifying the local names and translating them into scientific names (Figure 4.4c);

iv. Canopy cover was estimated by measuring the radius from stem stand to the edge of the canopy using a measuring tape and estimated the canopy cover (Asrat & Tesffaye, 2013; Barrett & Fried, 2004). This was done on both sides eventually getting the crown width. This was done also in the other direction and got the average. The crown area was estimated using the crown area formula (Loubota-Panzou & Feldpausch, 2020):

$$Crown\ area = ((crown\ width)/2)^2 \qquad \text{Eq. 10}$$

Added up the crown areas of all the trees in the sample plot to get the total canopy area covered by the trees. Then divided the total canopy area by the plot area (30m x 30m) and multiply by 100 to get the canopy cover percentage as follows:

$$Canopy\ cover\ (\%) = (Total\ camopy\ area/Plot\ area)\ x\ 100 \qquad \text{Eq. 11}$$

; and

v. Five evenly distributed, 10 cm soil samples (Figure 4.4d) were collected in 500 ml Ziplock bags. The bags were sent to UNZA, Geology Lab to sieve for particle size. This was done using a sieve shader with sieve sizes of 4.75 mm, 2.00 mm, 1.18 mm, 0.43 mm, 0.212 mm and 0.075 mm (Kangas & Maltamo, 2006). Additionally, ancillary information such as leaf size, bark texture and tree use were documented (Appendix 4, 5, 6, 7 and 8) to enrich the dataset and provide deeper insights into the characteristics of the identified species and forest types.

Figure 4.4: Data collection in the UKRSB, Zambia. (a) Measuring tree diameter; (b) Estimating tree height; (c) Identifying tree species and observing leaf size; and (d) Taking soil samples at 10 cm soil depth.

Indirect observation involved gathering data by attentively watching behaviours, events or recording physical characteristics within their natural context (Figure 4.5) (CDC, 2018; Taylor-Powell & Steele, 1996). On-site observation was undertaken in both the dry and wet seasons. Data collection involved the use of an Observation Sheets, provided in Appendix 2, which served as a structured template for recording observations (FAO, 2015). The Observation Sheets included predefined categories and prompts to guide the observer in documenting relevant information. Observations were directly recorded onto the sheet during the observation process. Field notes supplemented the structured data collected by providing additional context (cf. CDC, 2018).

Figure 4.5: Dry season on-site field observation, St. Anthony area in Mpongwe, Zambia.

4.6 Data Management and Analysis

Data collected from the systematic literature review, field observations, RS and forest inventory underwent organisation and analysis utilising a combination of software and statistical tools to ensure robustness and accuracy. For a systematic literature review, PRISMA guidelines were employed and the Visualisation Of Similarities Viewer (VOSviewer) version 1.6.20, a software tool, was employed for a bibliometric analysis (Van-Eck & Waltman, 2010; Linnenluecke et al., 2020; Moher et al., 2009). The co-authorship network visualisation map generated from VOSviewer provides a graphical representation of the collaborative relationships among authors who have contributed to the literature on the forest-water nexus (Van-Eck & Waltman, 2010). Qualitative data from field observations and notes were analysed thematically to extract key themes, insights and implications relevant to the research objectives.

Involving the RS data, QGIS desktop version 3.28.2 was utilised for spatial analysis (Galante et al., 2020). This involved processing the Landsat imagery and estimating ET rates using the SEBAL algorithm. The Landsat imagery spanning from January 2009 to December 2022, including precipitation data, time-series analysis techniques, such as trend analysis, seasonal decomposition and anomaly detection were applied to identify long-term trends, seasonal patterns and anomalous events in ET dynamics (Carr, 2008; Rahardja, 2021).

Field data collected through forest inventory and ground truthing exercises underwent verification analysis to cross-validate with existing literature and to validate RS results (Kangas & Maltamo, 2006). This involved examining parameters such as Diameter at Breast Height (DBH), height, species identification and canopy cover. Microsoft Excel version 2108 was employed for statistical analysis, including the calculation of descriptive statistics, correlation coefficients and graphical representation of data through graphs and tables (Carr, 2008).

4.7 Ethics

The study adhered to strict ethical guidelines set by the Natural and Applied Sciences Research Ethics Committee (NASREC) of the University of Zambia (UNZA). The research received formal ethical clearance under Approval No. NASREC-2022-JUL-017 (Appendix 9).

Ethical Considerations:

1. Informed Consent – Participants involved in the study, particularly in field surveys were required to provide written informed consent before participation. The consent process ensured that they understood the purpose, risks and benefits of the research.

2. Confidentiality and Data Protection – Personal and sensitive data collected during field surveys and community engagements were anonymised. Access to raw data was restricted to the research team and data were only used for academic purposes.

3. Environmental and Cultural Sensitivities – The study respected local environmental regulations and cultural traditions, particularly when conducting soil and vegetation sampling in forest reserves and communal lands. Necessary permits from forestry and local authorities were obtained before data collection.

4. Ethical Reporting and Compliance – The study followed ethical reporting guidelines, ensuring transparency and accuracy in findings. Ethical compliance was monitored through regular progress reports submitted every six months to NASREC as required.

5. Approval for Amendments and Extensions – Any modifications to the research methodology or additional data collection required prior approval from NASREC. The study approval was granted for one year, with provisions for renewal upon submission of a continuation application.

This ethical framework ensured that the research was conducted responsibly, minimized risks to participants and the environment, and upheld scientific integrity.

4.8 Limitations and Mitigation Strategies

Primary limitations of the study were the unavailability of high-resolution hydrological data. The research relied on satellite-derived AET, Precipitation, TCC, land cover and NDVI datasets, which inherently carry uncertainties. The absence of long-term flux tower data in the UKRSB further restricted the validation of remote sensing-derived hydrological parameters. To address this limitation, future research should integrate ground-based lysimeter measurements and eddy covariance flux tower data to enhance accuracy and validation of satellite-derived hydrological data.

Although data collection was conducted across two seasons, field-based observations were often hampered by weather conditions, particularly during the wet season. The unpredictability of rainfall limited accessibility to some forest inventory plots, which may have influenced data consistency. A recommended mitigation strategy is the deployment of continuous automated monitoring stations that can provide real-time hydrological and climatic data, minimising the challenges associated with seasonal constraints.

The study also encountered remote sensing classification errors, particularly in distinguishing woodland types. Despite the use of high-resolution Sentinel-2, some misclassifications may have occurred due to spectral similarities between certain forest classes. To improve classification

accuracy, future studies should incorporate UAV-based (drone) imagery and enhance field validation techniques to refine land cover classification models.

4.8.1 Delimitation of the Study

The study was geographically confined to the UKRSB focusing on assessing the forest-water-climate nexus within this specific region. The analysis was limited to Miombo/Chipya, Munga, Parinari and Kalahari woodlands, thereby excluding other land cover types that might have contributed to a broader understanding of forest-hydrology interactions. The temporal range of the study spanned from 1970 to 2023 for the systematic literature and 2009 to 2022 for remote sensing data which, while capturing important trends, may restrict long-term historical comparisons.

Furthermore, the study primarily concentrated on AET excluding groundwater modelling due to data limitations and scope constraints. Instrumentation constraints also posed a challenge, as the absence of sap flow meters restricted the precise quantification of individual tree transpiration rates. The scarcity of meteorological stations in the study area limited the validation of ET models such as SEBAL. Given these delimitations, the findings of this study are context-specific to the UKRSB and the selected timeframe, any extrapolation beyond these conditions should be approached with caution. Future research should expand both the geographical coverage and temporal scope, integrate additional hydrological parameters and leverage improved in-situ measurement techniques for a more comprehensive analysis.

4.9 Summary

Chapter Four outlines the methodology employed to achieve the study's objectives, focusing on a combination of systematic literature review, indirect on-site observations, RS data acquisition, forest inventory and ground truthing. A systematic literature review followed PRISMA guidelines, using Google Scholar to identify relevant research articles. Data was cleaned, organised and stored in RIS format for analysis. Indirect on-site observations involved structured data collection during both dry and wet seasons, using observation sheets and field notes. RS data was obtained through geeSEBAL, using the SEBAL algorithm on Google Earth Engine (GEE), with Landsat 7 and 8 images to estimate ET rates. A linear interpolation method was applied for data consistency. Forest inventory involved measuring Diameter at Breast Height (DBH), height (H), canopy cover and

species identification with assistance from the Forest Department and local guides. Ground truthing was used to validate RS data and ensure accurate sampling. Data management and analysis utilised various software tools, including QGIS for spatial analysis, VOSviewer for bibliometric analysis and Excel for statistical calculations. Ethical considerations were prioritised throughout the research, ensuring compliance with protocols and necessary permits were secured (Appendix 9).

CHAPTER FIVE: RESULTS, INTEPRETATION AND DISCUSSION

5.1 General Remarks

This chapter presents the results, interpretation and discussions of the research in the UKRSB, Zambia by addressing the research objectives and questions.

5.2 System Literature Review

Utilising google scholar, a total of 672 articles were initially identified. After applying inclusion and exclusion criteria, 25 articles were deemed relevant for the study (Figure 5.1).

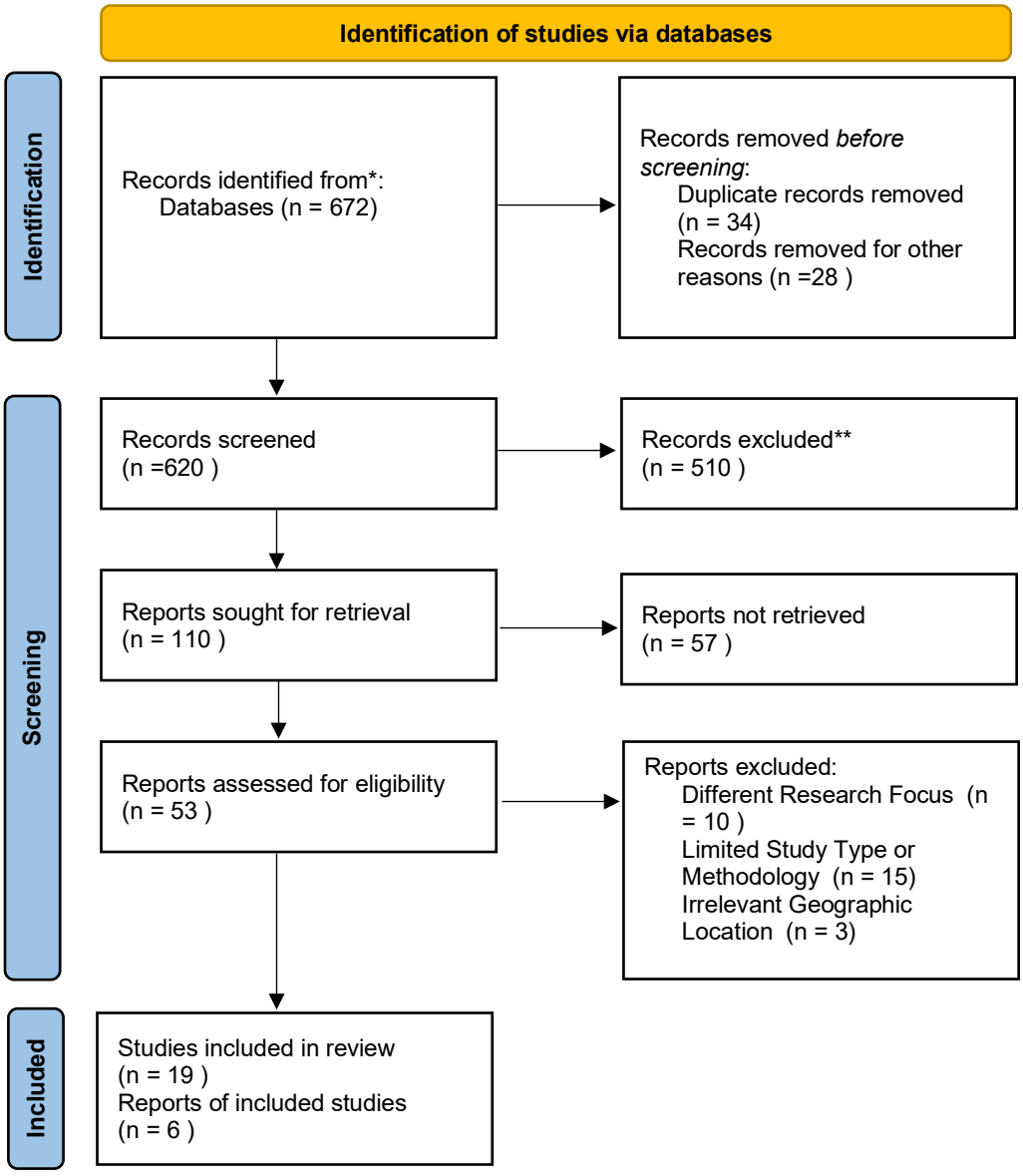

Figure 5.1: PRISMA 2020 flow diagram adopted from Moher et al. (2009) used in this study.

The review yielded a modest number of articles directly or indirectly addressing the forest-water nexus in Zambia. This suggests that, whereas some researches have been conducted on the topic, it remains relatively understudied within the Zambian context. Some of the earliest studies by Mumeka (1986) in the Luano Basin of the KRB in Zambia, reported that deforestation resulted in increased streamflow. This earlier perspective suggested that forest loss led to increased water availability in streams but subsequent research has provided a more nuanced view. Calder et al. (2007) challenged this finding, indicating that deforestation might initially increase streamflow but over time it can lead to a reduction in water resources due to soil degradation and altered hydrological processes.

The bibliometric analysis (Figure 5.2) further underscores this observation. Each node represents an author and the size of the node corresponds to the author's level of collaboration within the network (Van-Eck & Waltman, 2010). Additionally, the connections between nodes represent co-authorship relationships with thicker lines indicating stronger collaboration between authors (Van-Eck & Waltman, 2010).

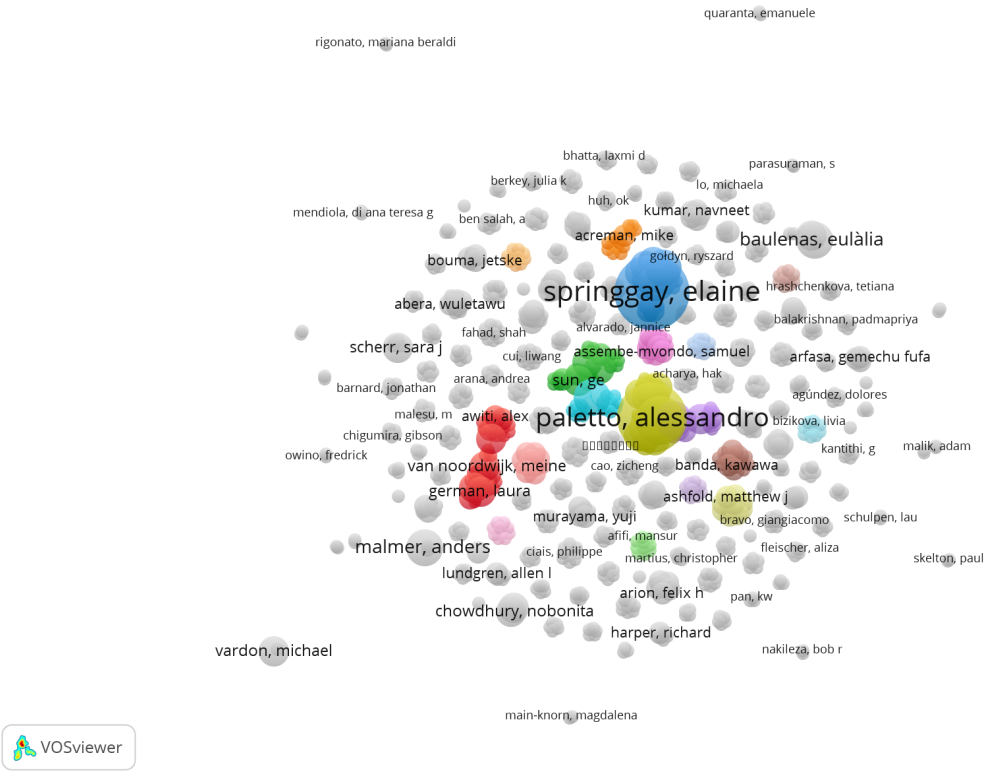

Figure 5.2: Co-authorship network visualisation for articles searched for the forest-water nexus, in the UKRSB, Zambia.

The emergence of distinct clusters in the co-authorship network reflects the diversity of research topics (Van-Eck & Waltman, 2019) within the forest-water nexus field. These clusters highlight specific themes that dominate the current body of research (Van-Eck & Waltman, 2019) such as forest cover, water quality and hydrological processes. The existence of these clusters suggests that researchers are focusing on distinct aspects of the forest-water nexus potentially leading to specialised knowledge and expertise in those areas. Central figures within these clusters, like Paletto and Springgay are pivotal to the co-authorship network. Their prominence suggests they have established expertise and a broad collaborative network within the forest-water nexus research community. Such central authors often play a key role in guiding research directions and fostering collaboration among other researchers as noted by Van-Eck & Waltman (2010). The importance of these central figures lies in their potential to serve as foundational references for further research. A study by Servia-Rodríguez et al. (2015) showed that central authors in a co-authorship network often act as hubs connecting disparate research areas and promoting interdisciplinary collaboration. This hub function is critical in a field like forest-water nexus where multidisciplinary approaches are essential to understanding complex ecological and hydrological relationships (FAO et al., 2021). The prominence within the co-authorship network also underscores the value of collaboration in advancing research. Their centrality indicates they have built extensive partnerships with other researchers enabling the sharing of ideas, data and methodologies. This collaborative spirit leads to innovative approaches and a more comprehensive understanding of the forest-water nexus (FAO, 2019).

The identification of co-authorship networks among researchers in the forest-water nexus field signifies a collaborative approach to tackling complex issues related to forests and water resources in the KRB. This network-based structure shows that researchers are not only exploring individual topics but are also engaging in collaborative efforts to deepen understanding and address pressing challenges. As noted by Van-Eck & Waltman (2019), clusters of authors grouped closely together on the map suggest tightly-knit collaborative networks indicating that these research teams share common interests and goals. Such clusters often represent research groups or collaborations among institutions that focus on specific themes (Anjum et al., 2020) within the forest-water nexus. This collaborative trend is an encouraging sign as it suggests that researchers are pooling their expertise and resources to conduct comprehensive studies, share data and validate findings. By working in close collaboration, teams can foster a more holistic understanding of the issues at hand. An

example of this collaborative approach is illustrated by the co-authorship article that analysed the impact of deforestation in the Kamfinsa River Basin within the KRB on water resources (Kasaro et al., 2019). This study explored how deforestation in the region affects streamflow and other aspects of the hydrological cycle. The co-authorship in this article indicates that researchers from various backgrounds are coming together to explore the effects of deforestation, a key concern in the KRB. Collaboration in these networks allows researchers to combine different methodologies and perspectives leading to more robust and comprehensive insights. A study by Liao (2011) suggest that collaborative networks often result in higher-quality research outcomes due to the diverse expertise involved. When applied to the forest-water nexus, such collaborations can contribute to better-informed policies and management practices, ultimately aiding in sustainable forest and water resource management.

Some authors appear as isolated nodes on the map, indicating limited collaboration with other researchers within the co-authorship network (Van-Eck & Waltman, 2010). Isolated nodes represent authors with specialised expertise or unique perspectives that are distinct from the broader research themes (de Stefano et al., 2011; Mena-Chalco et al., 2014; Qiu et al., 2014). One reason for isolated nodes might be geographical or institutional barriers (Morone et al., 2019). Authors based in remote regions or working at smaller institutions might have fewer opportunities to engage with broader research networks. Findings from Spithoven et al. (2021) indicate that geographical location can play a significant role in collaboration with researchers in more isolated areas having limited access to collaborative opportunities. Similarly, Matthews et al. (2020) observed that researchers from smaller institutions might lack the resources or networks necessary for broader collaborations. These isolated authors, despite limited collaboration could offer unique insights into the forest-water nexus in Zambia. A study by Celeste et al. (2014) shows that isolated researchers often bring fresh perspectives or explore unconventional methodologies, which can add significant value to the broader field. This research study therefore, suggests an opportunity to bridge gaps and foster more inclusive collaboration by connecting these isolated authors with the larger research community. More research is recommended for the forest-water nexus in Zambia for the understanding of the IBWT.

5.3 Field Observations

Deciduous trees predominantly comprising Miombo woodlands were noticed, while evergreen trees are primarily found in plantations (Figure 5.3a), notably managed by corporate organisations like Zambia Forestry and Forest Industries Corporation (ZAFFICO) in Mufulira and Ndola. Minimal invasive species were observed, with *Lantana camara* being notable (Constantine et al., 2022). The Kafue River serves as the main water body in the basin with tributaries such as the Kafubu River and seasonal streams contributing to its flow (Figure 5.3b), along with small lakes such as the Lake Kashiba (Figure 5.3c). Wildlife includes seasonal birds, crocodiles and hippos (Beilfuss & Kamweneshe, 2002; Cowx et al., 2018), yet there are signs of reduced biodiversity and less dense forest cover possibly due to logging, agriculture expansion (Figure 5.3d) and mining activities in areas like Luanshya and Mufulira coupled with charcoal production by indigenous communities (Kasaro et al., 2019).

Figure 5.3: Interwoven ecosystems in the UKRSB, Zambia. (a) Pine and Eucalyptus plantations (Ndola); (b) Seasonal stream that flows in the Kafue River (Mufulira); (c) Lake Kashiba (Mpongwe); and (d) Agriculture expansions (Mufulira).

It was observed that, the presence of *Nymphaeaceae*, commonly called water lilies was consistent in certain water streams. In particular, the observation of lilies associated with a notable decrease in water turbidity (cloudiness or haziness of the water stream) (Figure 5.4a and 5.4b).

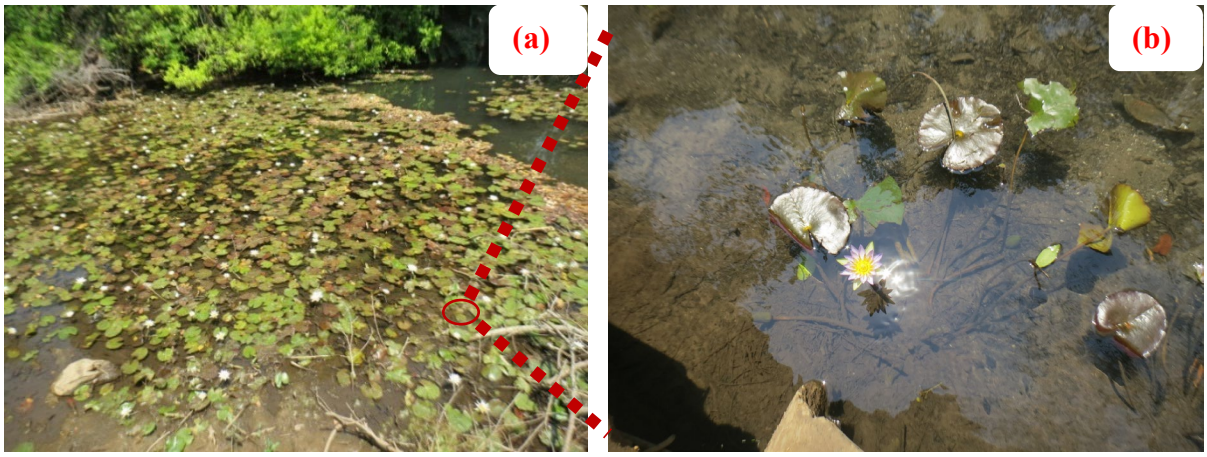

Figure 5.4: Image illustrating the observation of (a) *Nymphaeaceae* (Water lillies); and (b) A close-up view highlighting the clarity of water in their presence, Mpongwe, Zambia.

The observation of lilies positively influencing water quality aligns with findings from a study conducted by Dhote & Dixit (2009) who explored the role of aquatic macrophytes in water quality improvement. The research underlined the capacity of floating plants like lilies to significantly reduce turbidity as observed in the UKRSB study area. Other studies, such as those by Tani et al (2006) and Belmont et al (2004) demonstrated that the presence of lilies can lead to the removal of suspended solids and the improvement of water transparency through their intricate root systems and nutrient-absorbing capabilities. Water lilies with their extensive root systems can act as natural barriers and filters preventing sediment and pollutants from being carried along during IBWT. Lilies, possess the capacity to act as natural purifiers by stabilising the water environment in several ways (Tani et al., 2006). This root action effectively reduces the amount of soil and suspended particles that would otherwise contribute to water turbidity (Gupta et al., 2012). Lilies are efficient nutrient scavengers with the capacity to absorb excess nutrients particularly nitrogen and phosphorus (Chang et al., 2024). This nutrient uptake is essential in preventing eutrophication, which can lead to algal blooms and reduced water quality (Chang et al., 2024). The canopy of lilies floating on the water surface offers shade and cover, reducing sunlight penetration (Etnier et al., 2017). This shading effect limits the growth of harmful algae and aquatic plants, which can further

contribute to water clarity (Etnier et al., 2017). This ecological stability further enhances the overall health and quality of the water in the streams (DeWolf et al., 2022).

It was also observed that riparian forests along the banks of the Kafue River revealed variations between the dry and wet seasons. In the dry season, the riparian forests exhibited sparse vegetation cover with several exposed tree roots and patches of bare soil visible (Figure 5.5a). The riverbanks appeared eroded, with signs of sediment deposition in certain areas. Additionally, the water level was noticeably lower, exposing large expanses of riverbed. Conversely, during the wet season the riparian forests experienced a surge in vegetation growth with dense foliage covering the banks. The riverbanks appeared stabilised with reduced signs of erosion and sediment accumulation. The water level rose, submerging previously exposed areas of the riverbed and extending into the riparian zone (Figure 5.5b).

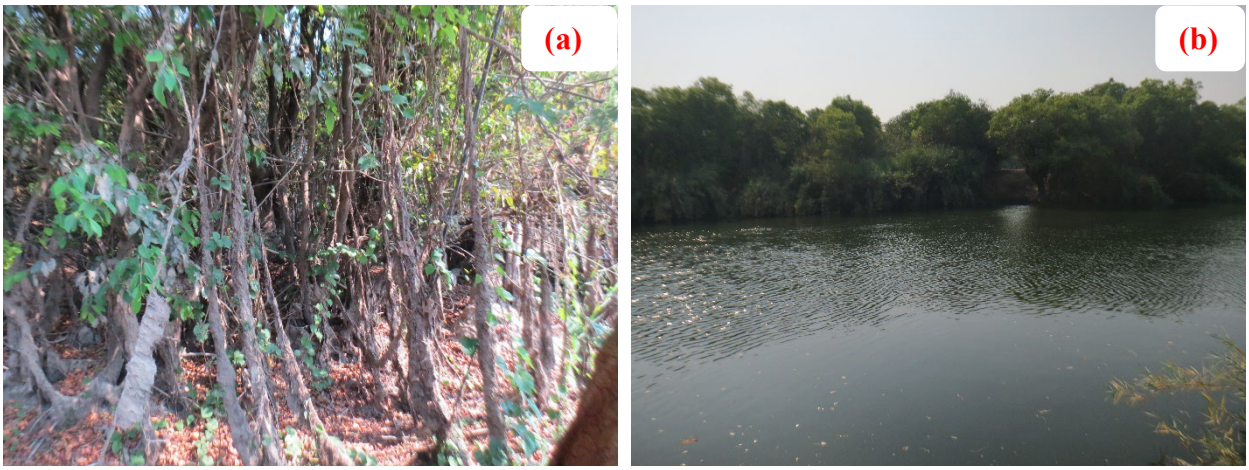

Figure 5.5: (a) Riparian forests in the dry season along the Kafue River, Luanshya, Zambia; and (b) in the wet season in the same area.

In the dry season, the sparse vegetation cover and exposed soil highlight the vulnerability of riparian ecosystems to water scarcity and erosion (García & Jáuregui, 2020). Conversely, in the wet season, the lush greenery and stabilised riverbanks demonstrate the resilience of riparian forests in response to increased water availability (Mpanyaro et al., 2024). The findings from this observation align with previous researchers. Studies have consistently shown that riparian forests play a critical role in regulating water quantity and quality by stabilising riverbanks, reducing erosion and filtering pollutants (García & Jáuregui, 2020; Mpanyaro et al., 2024). The observation of increased vegetation growth and reduced erosion during the wet season corroborates these

findings, highlighting the importance of riparian forests in mitigating the impacts of seasonal fluctuations in water levels. Furthermore, direct engagement with the riparian ecosystem allowed to witness first-hand the dynamic interactions between forests and water in the KRB. By bridging the gap between theory and reality, the observations provide valuable insights into the adaptive capacity of riparian forests to changing environmental conditions (Nakamura, 2022). These findings underscore the need for holistic management approaches that prioritise the conservation and restoration of riparian ecosystems to ensure the long-term sustainability of water resources in the UKRSB and similar riverine landscapes globally.

5.4 Spatial Distribution

The average annual ET for the year 2022 in the UKRSB was estimated to be 985 mm year^{-1}. However, there were variations across the study area. A representation of the distribution of annual AET (Figure 5.6), highlights areas with both high and low ET rates. The minimum rate recorded was 268 mm year^{-1} while the maximum reached 1505 mm year^{-1}. The impact of land cover on ET is evident in Figure 5.6. It illustrates AET rates (Figure 5.6a) alongside their corresponding land cover types (Figure 5.6b). Areas with rangeland and dense vegetation exhibit high AET values compared to barren or sparsely vegetated regions. The red areas contour lines highlight areas

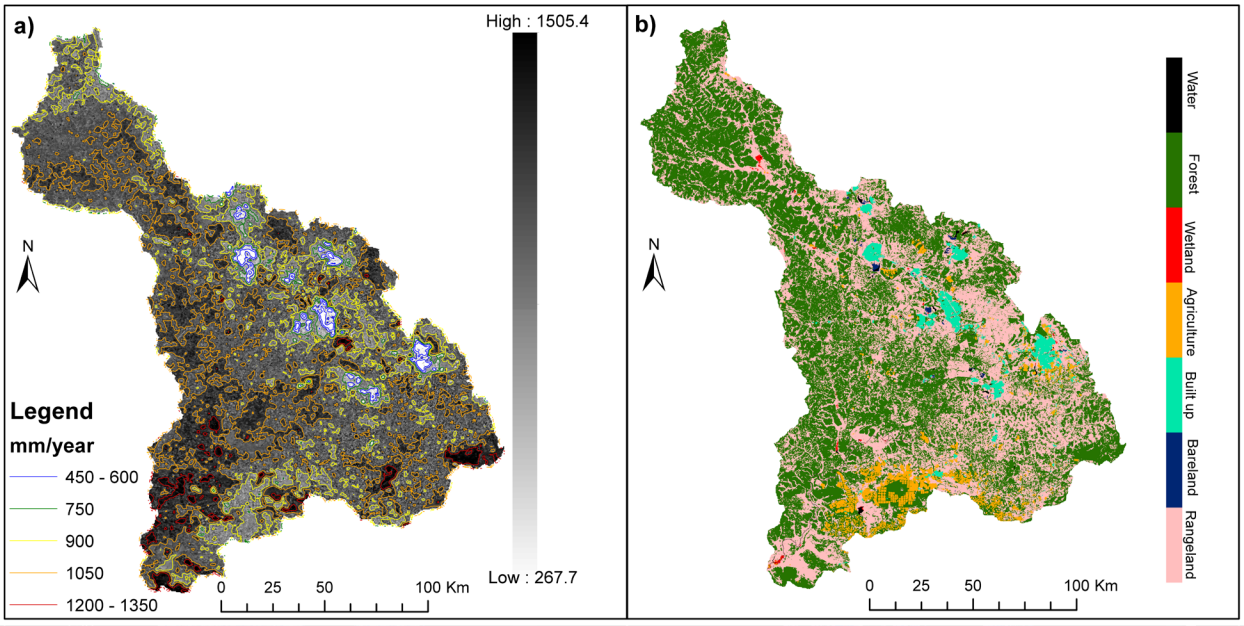

Figure 5.6: Side-by-side maps for the UKRSB, Zambia for the year 2022. (a) Depicting the distribution of AET rates, superimposed with contour lines derived from areas of similar rates; and (b) corresponding land cover types (ESRI Inc, 2022).

within the UKRSB with elevated AET rates ranging from 1200 mm year^{-1} to 1350 mm year^{-1}, primarily located in the southern part of the study area.

When analysing patterns, it was observed, differences in AET rates between dry and wet seasons. Table 5.1 presents data on variability which emphasises how climatic conditions impact ET dynamics.

Table 5.1: A summary of the seasonal distribution of AET in the UKRSB in Zambia 2022.

Variables	**Dry Season (May to early November)**	**Wet Season (December to April)**
Mean (mm month^{-1})	73	96
Min (mm month $^{-1}$)	6	20
Max (mm month^{-1})	200	177

In the dry season, the mean AET was recorded at 73 mm month^{-1}, with a minimum of 6 mm/month and a maximum of 200 mm month^{-1}. In contrast, the wet season exhibited higher AET rates, with a mean of 96 mm month^{-1}, a minimum of 20 mm month^{-1} and a maximum of 177 mm month^{-1}. These variations underscore the distinct impact of climatic conditions on ET processes in the UKRSB. The higher AET rates during the wet season can be attributed to increased moisture availability, while lower rates during the dry season reflect water stress conditions. These findings are consistent with studies by Bastiaanssen et al. (2005) and Zimba et al. (2023), which emphasise the seasonality of ET dynamics in semi-arid regions. Mwelwa (2004) also highlighted in her study in the KRB that ET rates exhibit a relatively constant pattern of 6 mm day^{-1} during the wet season and decreases to 4 mm day^{-1} in the dry season. That, this variation is due to moderating effects of increased cloud cover and atmospheric vapour pressure during the wet season compared to the lower temperature, clearer skies and atmospheric conditions of the dry season (Mwelwa, 2004).

The spatial distribution of AET was classified into land cover types based on contribution of each land cover (Figure 5.7).

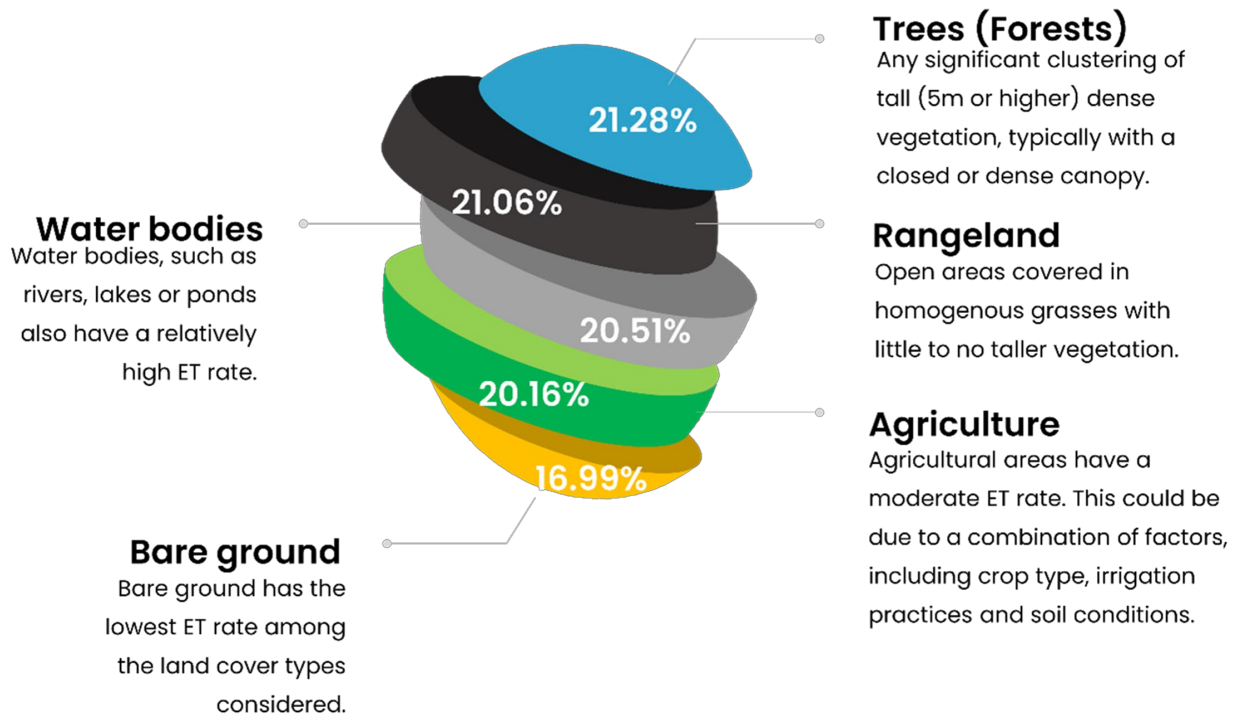

Figure 5.7: Proportional contribution of land cover to AET in the UKRSB, Zambia

Trees (forests) account for 21.28% of the area studied. This category represents regions characterised by clustering of vegetation (5m or higher) with a closed or dense canopy. Forested areas demonstrate high AET rates highlighting their important role, in water dynamics (Zimba et al., 2022a). Rangeland, which refers to areas covered in grasses without taller vegetation, like trees or shrubs demonstrated an AET rate of 21.06%. These rangeland regions spanning across the United States of America, Burkina Faso, Kenya, Kyrgyzstan, Niger and Uruguay have been observed to influence the water balance as noted by Onyango et al. (2022) and Wilcox et al. (2003). Water bodies, such as rivers, lakes or ponds exhibited an AET rate of 20.51% highlighting the impact of water surfaces on hydrology at both local and regional scales. Agriculture areas displayed an ET rate of 20.16% influenced by factors like crop types, irrigation practices and soil conditions. Agricultural activities contributed to 20.16% of the AET observed in the study area. On the other hand, bare ground had the lowest AET rate among all land cover types considered at 16.99%. This is expected since the absence of vegetation limits transpiration and evaporation (Bastiaanssen et al., 2005).

These findings align with previous research emphasising the relationship between land cover and ET rates. A study by Turk et al. (2021) provides a similar analysis of ET in the Eastern Region of Saudi Arabia, using SEBAL and Landsat-8 satellite data to estimate actual daily, monthly and annual ET for different land-use systems. The study identified six land-use types: date palm, cropland, bare land, urban land, aquatic vegetation and open water bodies. The results showed that ET values were higher in open water (2000 mm year^{-1}), compared to other land uses like cropland (800 mm year^{-1}) and date palm (800-1400 mm year^{-1}). These findings align with the research's results, reinforcing that land cover significantly influences ET rates, with forests contributing to higher ET (Breil et al., 2021). Similarly, Tena et al. (2019) in the Chongwe River Basin, assessed the impact of Land-Use/Land-Cover (LULC) changes on the hydrology including streamflow and ET. The study used Landsat imagery to track changes in LULC and the Water Evaluation and Planning (WEAP) model to simulate hydrological components. The findings indicated that forest land decreased by 41.11%, leading to a corresponding decrease in annual AET from 840.6 mm year^{-1} to 796.3 mm year^{-1} between 1984 and 2017. These results further support the notion that land cover changes can significantly impact ET rates, with deforestation and changes in LULC reducing ET.

The findings also indicate that AET within the UKRSB in Zambia for the year 2022 exhibited a heterogeneous spatial distribution. The average AET is estimated to be around 985 mm year^{-1} with variations ranging from a minimum of 268 mm year^{-1} to a maximum of 1505 mm year^{-1}. These differences can be attributed to the varying land cover types and climatic conditions across the area under investigation (Turk et al., 2021). It is evident that land cover has an impact on AET with forests and rangeland showing high AET values compared to barren or sparse vegetated areas (Bastiaanssen et al., 2005). Additionally, water bodies such as rivers, lakes or ponds also making significant contributions to AET. These findings are in alignment with studies that highlight how different types of land cover and plant phenology can affect water flow and hydrological processes (Tena et al., 2019; Turk et al., 2021; Zimba et al., 2023).

5.5 Correlation Between AET and NDVI

A scatter plot (Figure 5.8), displays the relationship between AET and NDVI. While it shows some dispersion of data points, it illustrates the overall trend of increased AET with higher NDVI values.

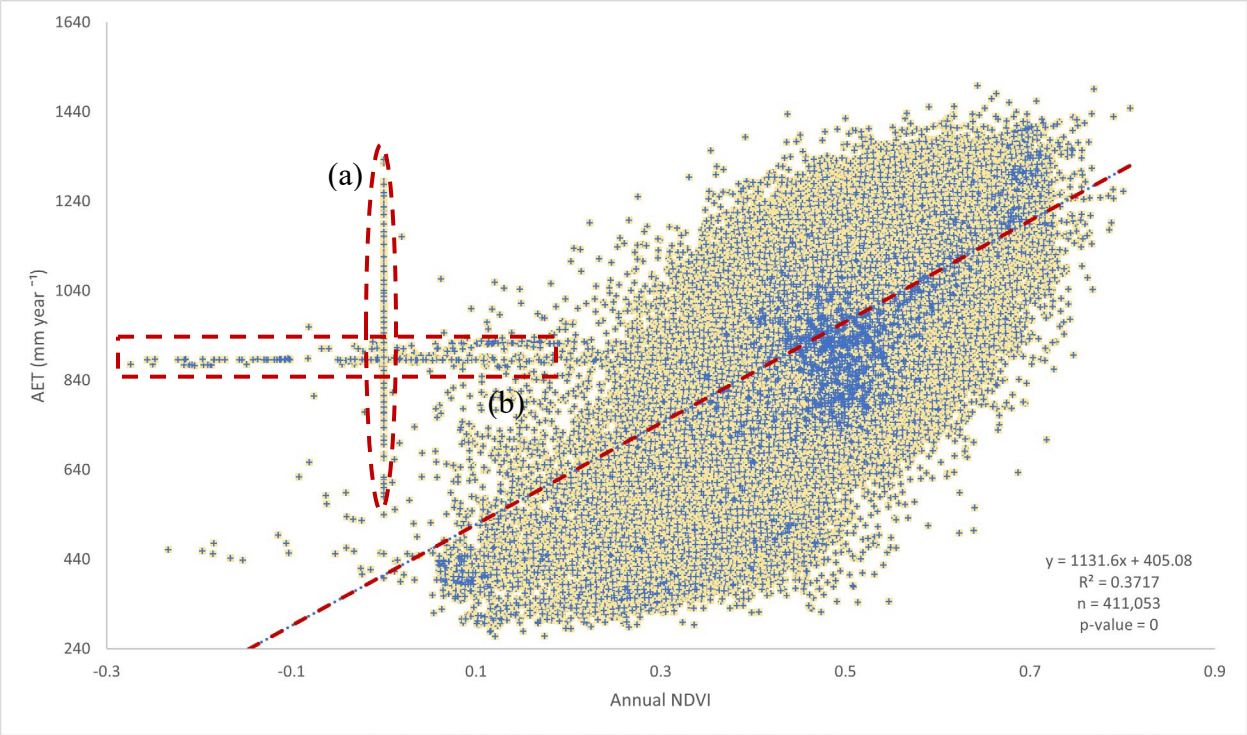

Figure 5.8: Annual correlation of AET and NDVI in the UKRSB, Zambia (2022) with two notable anomalies, (a) a constant NDVI of zero while AET increases from 572 to 1333 mm year^{-1}; and (b) a perpendicular rise in NDVI from –0.2 to 0.7 at a fixed AET of 886 mm year^{-1}.

The coefficient of determination (r^2) was found to be 37%. This result suggests a relatively weak positive correlation between AET and NDVI. This result aligns with a similar observation in a study focusing on the Western United States, where the correlation between AET and NDVI was lower than expected. Despite using the Simplified Surface Energy Balance (SSEB) model and the MODIS satellite data to estimate AET, the correlation was weak due to an eastward two to three kilometre shift in the data. This finding suggests that inaccuracies or inconsistencies in satellite-derived data can impact the strength of the correlation, leading to a weaker relationship between AET and NDVI than anticipated. A study by Phiri et al. (2013) in the semiarid Barotse Basin of South-Western Zambia, which used the SEBS model to estimate AET, provides additional insights into the ET-NDVI relationship. This study highlighted that NDVI-based roughness parameters could significantly affect AET estimates, leading to reductions in fluxes by up to 1.5 mm day^{-1} in forest areas compared to other parametrisations (Phiri et al., 2013). Phiri's study shows that the

highest AET rates were observed in areas with dense vegetation, such as regularly flooded zones and water bodies, indicating a link between high NDVI and increased AET.

In Figure 5.8 above, two notable anomalies are observed:

i. A constant NDVI with increasing AET (Figure 5.8a). NDVI remains constantly at zero whereas AET increases from 572 mm year^{-1} to about 1333 mm year^{-1}. This anomaly suggests that there are areas within the study region where vegetation is either absent or severely stressed, resulting in an NDVI value of zero. This could be due to non-vegetative factors contributing to AET, such as soil evaporation or open water bodies that contribute to AET independently of NDVI. NDVI values generally range from -1.0 to 1.0. Negative values indicate the presence of clouds and water, whereas values close to zero represent bare soil (Kourouma et al., 2022); and

ii. Perpendicular increase in NDVI at a fixed AET (Figure 5.8b). This shows an NDVI value increasing from -0.2 to 0.7 at a constant AET of 886 mm year^{-1}. This perpendicular rise in NDVI suggests a change in vegetation cover or type that alters NDVI without affecting the overall AET. Such an occurrence could be indicative of land use changes or the introduction of new vegetation types with different spectral properties, abruptly altering NDVI values while AET remains stable.

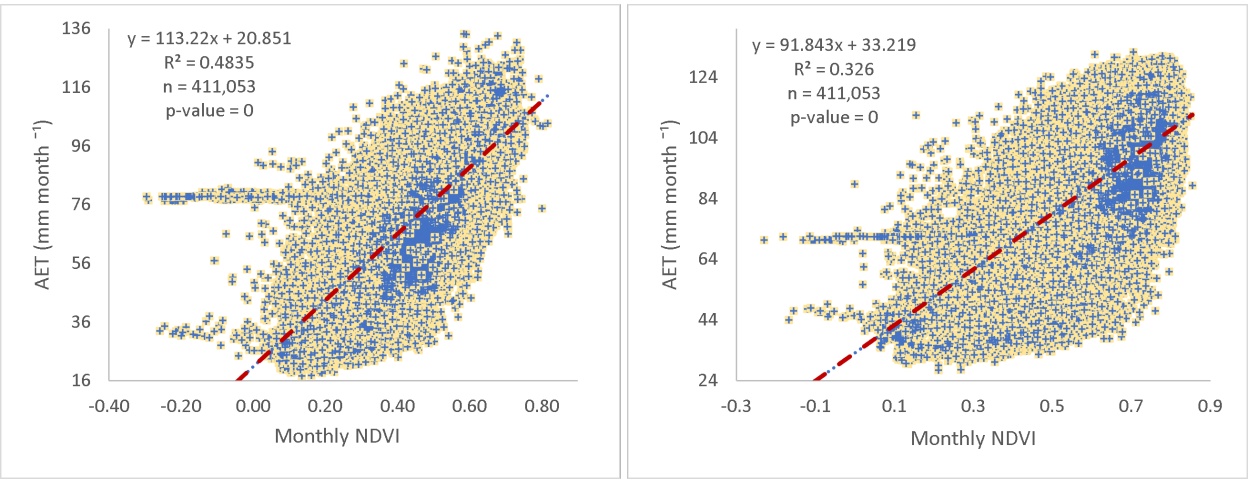

Figure 5.9: Scatter plots showing relationship between AET and NDVI during the Dry season (a) and Wet season (b).

In the scatter plot Figure 5.9 above, the dry season (Figure 5.9a) showed r^2 value of 0.48, indicating a moderate correlation between AET and NDVI. The wet season (Figure 5.9b) exhibited a lower r^2 value of 0.32, suggesting a weaker correlation during this period. The relatively higher r^2 value during the dry season suggests that AET and NDVI are more closely related when soil moisture is decreasing and vegetation is under stress due to limited water availability. This finding aligns with the idea that during dry periods, the vegetation's condition and water use efficiency become more closely linked (Bhattacharya, 2019), as reflected in the NDVI and AET values.

The findings indicate a moderate correlation between AET and NDVI during the dry season and a weaker correlation during the wet season. This is contrary to the study by Arast et al. (2020), which found that the correlation between NDVI and AET was generally stronger during wet seasons in the Zayanderud Basin, Iran. In their study, Arast et al. (2020) observed that seasonal variations had a notable impact on the correlation between NDVI, groundwater levels and AET with a stronger correlation in wet seasons compared to dry seasons. Despite the different climatic zones, the results from UKRSB, Zambia suggest that the relationship between AET and NDVI can vary with seasonal changes. The moderate correlation during the dry season might reflect the vegetation's response to decreased soil moisture and potentially reduced ET. This indicates a complex interaction between groundwater availability and surface vegetation, where the vegetation's health and water use are more tightly coupled during periods of water stress (Bhattacharya, 2019). The weaker correlation observed in the wet season in UKRSB could be attributed to several factors, including the abundant water availability which makes AET less dependent on NDVI, as vegetation is less stressed and can transpire more freely. This nuance underscores the need for a detailed understanding of how climatic conditions and water availability influence the relationship between vegetation and evapotranspiration across different regions and seasons.

Further analysis (Figure 5.10) in different woodlands of the UKRSB for the year 2022 revealed the following r^2 values:

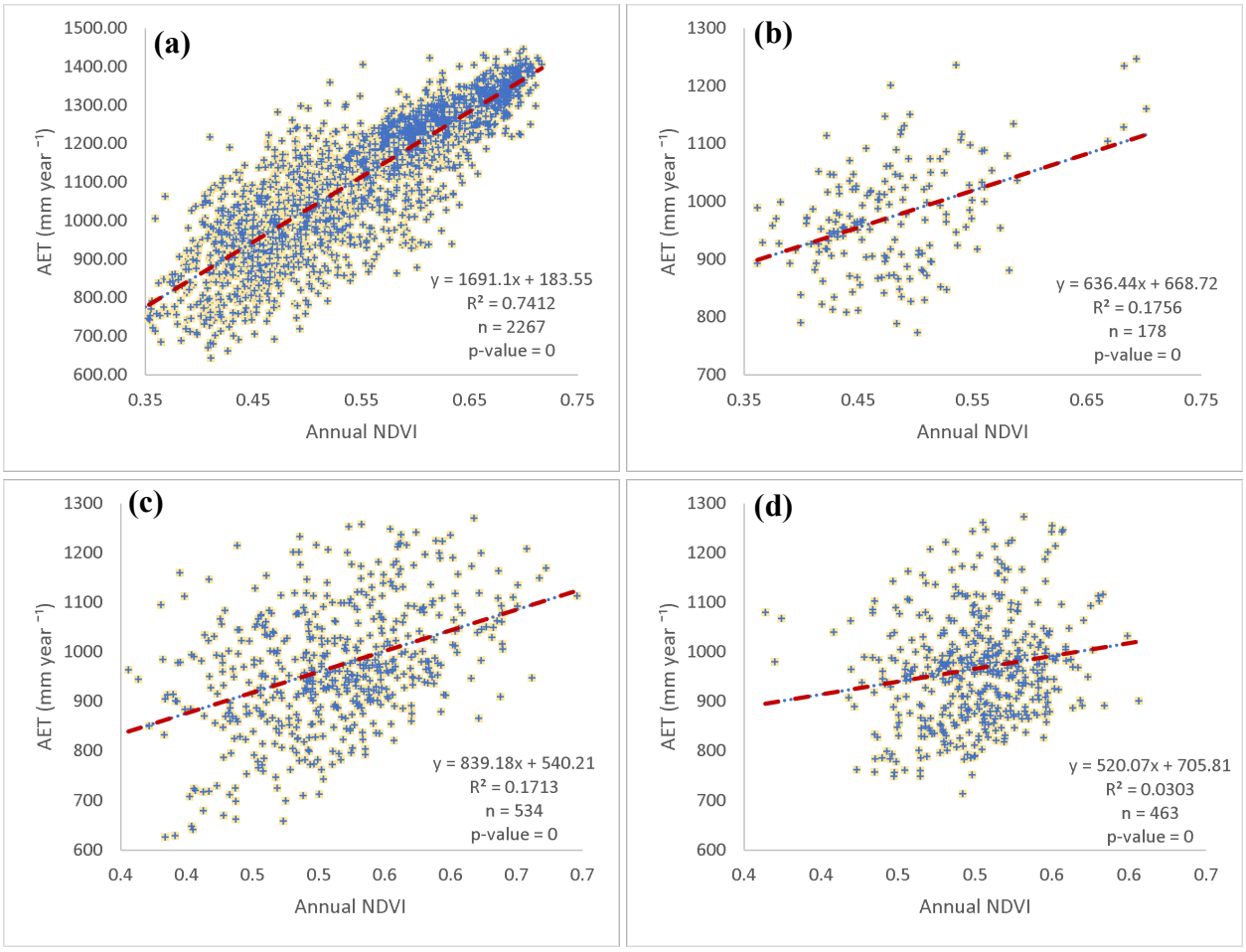

Figure 5.10: AET and NDVI relationship in different woodlands of the UKRSB, Zambia; a) Kalahari Woodland; b) Munga Woodland; c) Miombo/Chipya Woodland; and d) Parinari Woodland.

i. Kalahari Woodland $r^2 = 0.74$, n = 2267 and p-value = 0 (Figure 5.10a);

ii. Munga Woodland $r^2 = 0.17$, n = 178 and p-value = 0 (Figure 5.10b);

iii. Miombo/Chipya Woodland $r^2 = 0.17$, n = 534 and p-value = 0 (Figure 5.10c); and

iv. Parinari Woodland $r^2 = 0.03$, n = 463 and p-value = 0 (Figure 5.10d)

The results indicate a strong positive correlation between AET and NDVI in the Kalahari Woodland with r^2 value of 0.74. This suggests that in this type of woodland, NDVI is a good

predictor of AET and there is a strong relationship between vegetation health and water use. This finding aligns with Maselli et al. (2020) whose study demonstrated the effectiveness of an improved NDVI-based method to predict AET in Mediterranean grasslands and croplands: Pescia and Roselle, Italy. Maselli's method, which separately estimates vegetation transpiration and bare soil evaporation using Fractional Vegetation Cover (FVC) derived from NDVI, accurately accounted for additional water supply in irrigated conditions improving AET estimation accuracy. On the other hand, the Munga and Miombo/Chipya woodlands both show a weak positive correlation with r^2 values of 0.17, indicating that in these woodlands the relationship between NDVI and AET is relatively weak, suggesting that factors other than NDVI might be influencing AET. The Parinari Woodland shows a very weak correlation with an r^2 value of 0.03, suggesting no relationship between NDVI and AET in this woodland type, indicating that NDVI is not a good predictor of AET here and that other factors are likely playing a more significant role in determining AET. Its low AET rates further underscores that factors other than vegetation greenness predominantly influence ET in these areas. Effective water conservation strategies in such woodlands should therefore consider a broader range of environmental variables and not rely solely on NDVI as an indicator of water use and evapotranspiration rates.

5.6 Temporal Distribution

In terms of temporal distribution, Figure 5.11 showcases average AET rates from October to September hydrological year within the study period (Appendix 10). The results reveal patterns and variations in AET throughout these years with a recurring threshold value of 80 mm $month^{-1}$ observed over the entire ten-years period. Between October to April the rates of AET consistently went above the 80 mm $month^{-1}$ threshold (Figure 5.11a). These periods correspond to the wet seasons phases, where climatic conditions are conducive to higher rates of ET. The elevation of AET rates above the threshold during these times suggests enhanced moisture availability and increased vegetative activity, contributing to elevated water loss (Mwelwa, 2004). On the other hand, during the period from May to September, AET rates consistently remained below that established threshold (Figure 5.11b). This period coincides with the peak of the dry season, characterised by reduced precipitation and limited moisture availability (Mwelwa, 2004). Consequently, vegetation undergoes stress-induced dormancy or reduced metabolic activity, resulting in lower rates of ET (Zimba et al., 2022a).

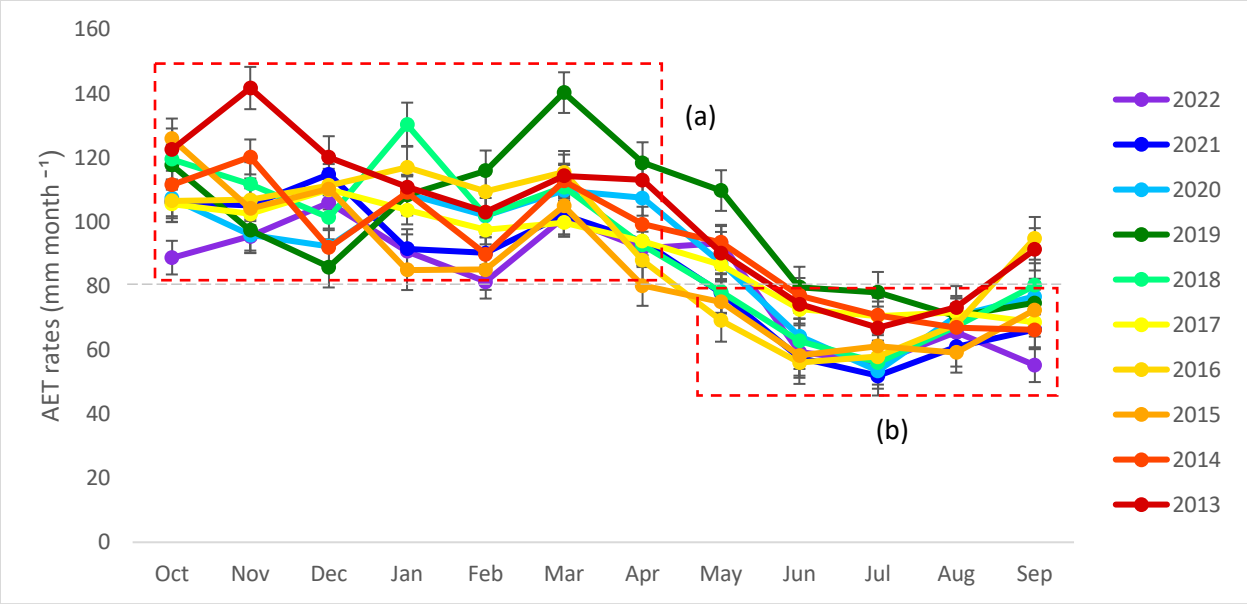

Figure 5.11: Monthly average temporal distribution rates of AET over a decade for the UKRSB in Zambia.

The recurring threshold of 80 mm month^{-1} serves as a useful reference point for delineating periods of heightened and subdued ET activity. These findings align with previous research on seasonal variations in ET dynamics. A study by Mwelwa (2004) in the KRB, Zambia demonstrated similar patterns as stated in Chapter 5, sub-section 5.4 of this thesis. Furthermore, a study by Wu et al. (2021) focused on the PT and PM equations to monitor regional ET in five sites across Australia and China, examining seasonal changes in ET coefficients. The research showed that while higher AET does not necessarily lead to higher PT and PM coefficients, average ET is typically higher in summer than in winter for all sites (Wu et al., 2021). This seasonal trend supports the findings of this research, reinforcing the idea that ET activity is influenced by seasonal factors and that summer typically experiences greater ET due to increased temperatures and vegetation growth. Additionally, from October to April for the ten years period, the average AET rates is 105.08 mm month^{-1}. This seasonal time is above the observed threshold. To offset this and maintain a threshold at 80 mm month^{-1}, a surplus of 25.08 mm month^{-1} is needed. This translates to 0.62 billion m^3 month^{-1} for October to September, resulting a total of 4.36 billion m^3 year^{-1}.

The graph (Figure 5.12) presents the annual difference between precipitation (inflow) and ET (outflow) over the period spanning from 2013 to 2022 in the UKRSB of Zambia. It reveals varying relationships between precipitation and AET indicating fluctuations in water balance dynamics over the decade.

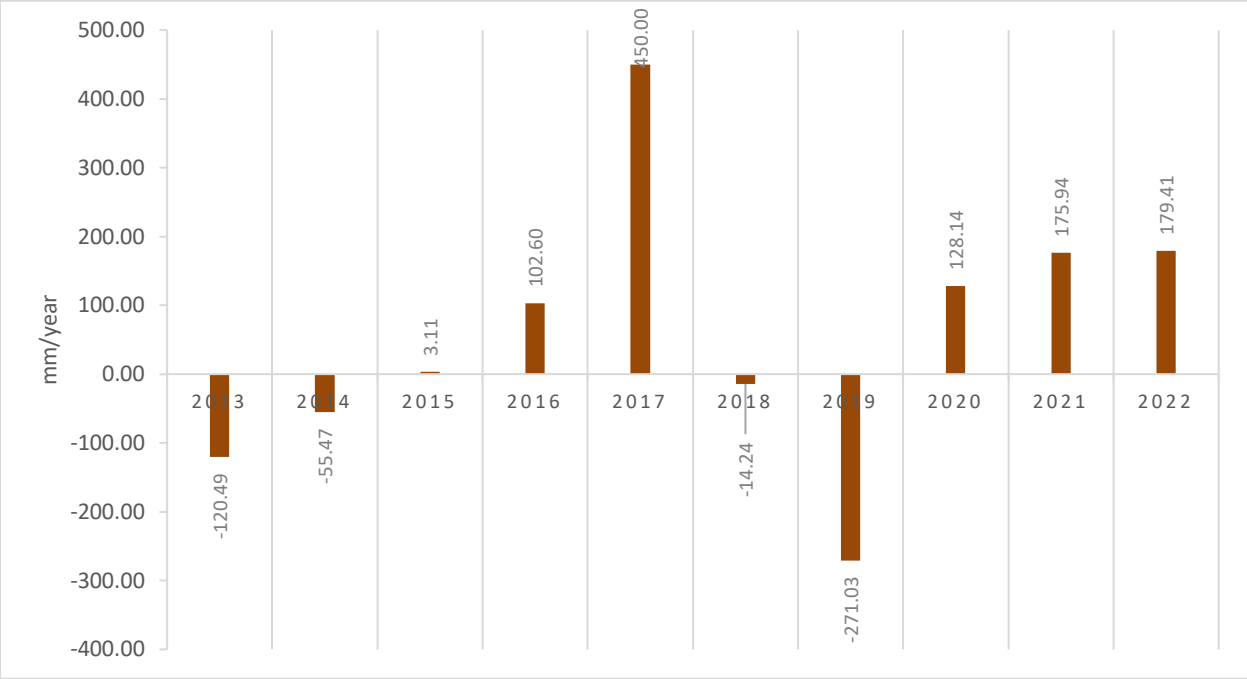

Figure 5.12: Annual differences of precipitation and AET from 2013 – 2022 of the UKRSB, Zambia.

In the years; 2013, 2014, 2018 and 2019 precipitation levels consistently fell below AET values resulting in negative differences. Precipitation recorded during those years was respectively documented at levels of 1101.06 mm year^{-1}, 1053.60 mm year^{-1}, 1098.53 mm year^{-1} and 925.15 mm year^{-1} while corresponding AET values were approximately 1221.55 mm year^{-1}, 1109.07 mm year^{-1}, 1112.77 mm year^{-1} and 1196.18 mm year^{-1} (Table 5.2). Conversely in the years; 2015, 2016, 2017, 2020, 2021 and 2022 positive differences were observed indicating an excess of precipitation. Further examination of Table 5.2 elucidates the variability in precipitation and AET values across the analysed years. Precipitation levels ranged from 925.15 mm year^{-1} to 1532.90 mm year^{-1}, while corresponding AET values ranged from 984.75 mm year^{-1} to 1221.55 mm year^{-1}. Notably, approximately 97% of the precipitation was returned as AET over the ten-year period. Reinforcing findings by Nsiah et al (2021), Sharma (1988) and JICA & MEWD (1995) in Ghana, Central Africa and Zambia respectively.

Table 5.2: Annual precipitation against annual AET over a 10 years period in the UKRSB, Zambia (FAO, 2023; Laipelt et al., 2021).

	Precipitation (mm year^{-1})	**AET** (mm year^{-1})
2013	1101.06	1221.55
2014	1053.60	1109.07
2015	1024.42	1021.31
2016	1202.81	1100.21
2017	1532.90	1082.90
2018	1098.53	1112.77
2019	925.15	1196.18
2020	1203.07	1074.94
2021	1191.55	1015.61
2022	1164.16	984.75

The observed negative differences in certain years indicate periods of water deficit, where ET exceeds precipitation, potentially leading to decreased soil moisture levels and heightened risk of drought. When ET consistently surpasses precipitation, land cover classes in these scenarios become net consumers of water resources, potentially exacerbating water scarcity and impacting local ecosystems (Bastiaanssen et al., 2012). This agrees with literature in chapter 2, sub-section 2.4.5, that Zambia is in a hydrological condition of precipitation deficit, amounting -100 mm year^{-1} to -1100 mm year^{-1} (JICA & MEWD, 1995). The total deficit is -461.23 mm year^{-1}. Conversely, the positive differences observed in other years suggest an excess of precipitation relative to ET, potentially leading to increased surface runoff, groundwater recharge and replenishment of soil moisture reserves. The deficit is recovered by1039.2 mm year^{-1} total surplus. Robertson (2005) and Ashaolu & Iroye (2018) demonstrate similar patterns of interannual variability in precipitation and ET in Zambia, Namibia, Zimbabwe, Nigeria and Botswana, thus supporting the existing understanding of climate variability and hydrological processes in semi-arid regions. Specifically, Robertson (2005) discusses rainfall and evaporation trends within the Four Corners area (Zambia, Namibia, Zimbabwe and Botswana) in southern Africa, where the majority of rain falls within a 5 months wet season. Evaporation typically exceeds rainfall in most months of the year, with Potential Evapotranspiration (PET) based on the Penman-Monteith (PM) formula ranging from 1650 mm year^{-1} in northern Zambia to over 1800 mm year^{-1} in the hot, low-lying areas around Victoria Falls (Robertson, 2005). This relationship highlights that in arid and semi-arid regions,

evaporation often surpasses rainfall leading to water deficits and increased pressure on water resources (Robertson, 2005). Moreover, the coefficient of variation for annual rainfall is relatively high, ranging from 15-20% in northern Zambia to over 35% in other parts of southern Africa, indicating significant fluctuations in water availability (Robertson, 2005). Ashaolu & Iroye (2018) examined climatic water balance and aridity in the Western Lithoral hydrological zone of Nigeria over a 40-year period from 1976 to 2015, using data from six meteorological stations. The study focused on rainfall, temperature, sunshine hours, relative humidity and wind speed applying the FAO-PM method to estimate PET (Ashaolu & Iroye, 2018). The results showed a statistically significant upward trend in both rainfall and PET during the study period. There were six months of water surplus (May-October) and six months of water deficit (November-April), with 27 years of water deficit in the 40-year period (Ashaolu & Iroye, 2018). Despite the trends, the mean Aridity Index (AI) of 0.94 indicated a generally humid environment, though the northern part was trending toward dry sub-humid conditions (Ashaolu & Iroye, 2018).

The temporal distribution of AET rates in the UKRSB from 2009 to 2022 indicates a decline over time as evidenced by a slope of -12.143 (Figure 5.13). The statistical significance of this trend is confirmed by a P-Value of 0.016 highlighting its reliability and robustness. This decline suggests shifts in conditions or land use practices (Mulenga et al., 2017). Several studies point out how land use changes, anthropogenic activities, climate and deforestation have impacts on ecosystems (Creed & Noordwijk, 2018; Kasaro et al., 2019).

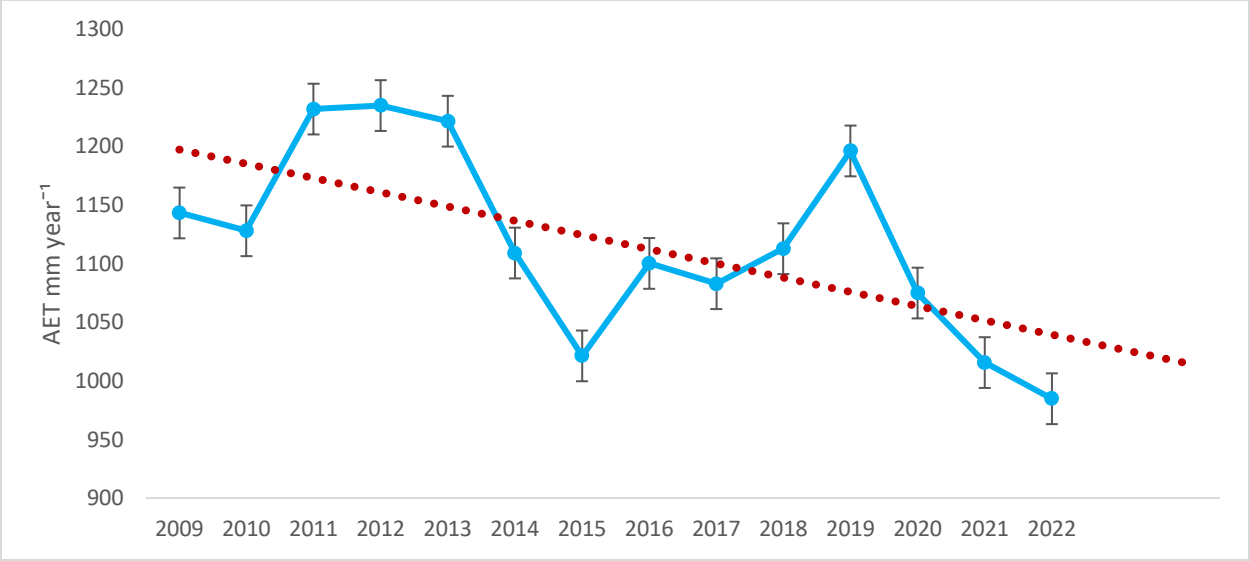

Figure 5.13: Annual average temporal distribution of AET from 2009 to 2022 for the UKRSB in Zambia.

Given the significance of forests in regulating water processes, any substantial loss of forest cover whether due to logging or wildfire can lead to reduced transpiration rates impacting AET (Ellison et al., 2017). With a deforestation rate of 576.3 ha year^{-1} in the KRB, not only does it correspond to the high emissions of carbon, as indicated by Kasaro et al. (2019), but also disrupts the hydraulic cycle and the rates of AET. Yang et al. (2016) found a 31-year decline in ET over China's Loess Plateau, with rates decreasing by 0.78 mm year^{-1}, largely due to reduced precipitation and humidity. The decline was more pronounced in semiarid regions, with summer experiencing the sharpest drop (Yang et al., 2016). Similarly, in the UKRSB, a drop in rainfall was observed alongside a decline in AET indicating a possible link between reduced precipitation and lower ET rates. Kourouma et al. (2022) points to a different dynamic: from 1983 to 2020, PET increased in the UKRSB by 0.04%, contributing to an AI of 0.60 and a moisture deficit index of −0.42. This pattern is often a sign of drought conditions (Kirkham, 2023; Kourouma et al., 2022). A drop in AET, with rising PET, suggests that there isn't enough water available for vegetation to meet its full ET potential (Kirkham, 2023). This leads to water stress for plants, affecting their growth and health (Basso & Ritchie, 2018).

5.7 Analysis of AET Rates across Woodland Ecosystems

The bar chart (Figure 5.14) shows the varying rates of AET observed in Parinari Woodland (WL1), Miombo/Chipya Woodland (WL2), Munga Woodland (WL3) and Kalahari Woodland (WL4).

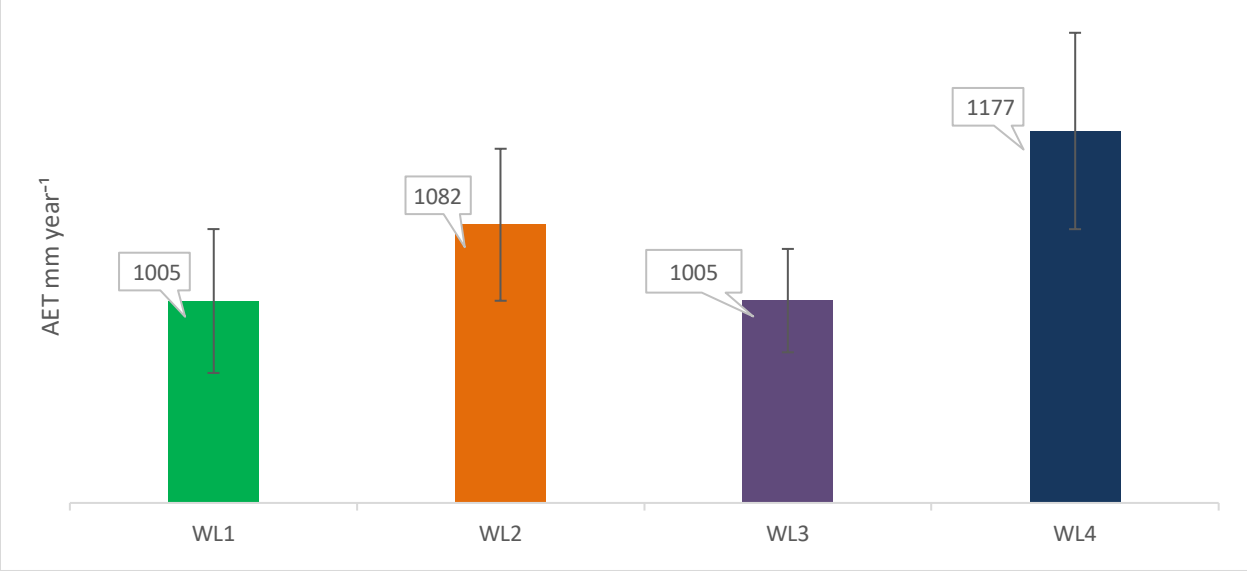

Figure 5.14: Average annual AET rates (mm) across different woodlands (WL) in the UKRSB in Zambia (2013-2022).

WL1 and WL3 have AET rates both measuring around 1005 mm year^{-1} while WL2 has a higher rate at approximately 1082 mm year^{-1}. On the other hand, WL4 stands out with a higher AET rate of about 1177 mm year^{-1}.

The descriptive statistics provided in Table 5.3 offer information on the AET rates for each woodland including measures, like mean AET rates, standard error, standard deviation and other relevant data. Moreover, the study also includes 95% confidence intervals (CIs) to indicate the precision surrounding these estimates.

Table 5.3: Descriptive statistics for the average annual AET rates (mm year^{-1}) across different woodlands (WL) in the UKRSB, Zambia.

Variables	**WL1**	**WL2**	**WL3**	**WL4**
Mean	1004.89	1082.28	1005.31	1177.44
Standard Error	23.08	24.38	16.59	31.51
Median	990.65	1079.98	1000.23	1170.97
Standard Deviation	73.00	77.11	52.45	99.64
Range	253.93	263.41	180.50	343.90
Minimum	910.49	964.78	922.29	1034.65
Maximum	1164.42	1228.19	1102.79	1378.54
Confidence Level (95%)	**52.22**	**55.16**	**37.52**	**71.28**
Upper Ci (95%)	**1057.11**	**1137.45**	**1042.83**	**1248.72**
Lower Ci (95%)	**952.67**	**1027.12**	**967.78**	**1106.16**

The observed variations in AET rates among different woodlands reflect the diverse ecological characteristics and hydrological processes inherent to each ecosystem (Breil et al., 2021; Zimba et al., 2023). WL1 and WL3 demonstrate comparable AET rates, suggesting similar levels of water loss through ET despite potential differences in vegetation composition and density. In contrast, WL2 exhibits a slightly higher AET rate, which may be attributed to differences in vegetation structure, soil moisture retention or microclimate conditions. Similarly, Kalahari Woodland (WL4) stands out with a significantly higher AET rate, likely influenced by unique ecological features such as deeper soil profiles or access to groundwater sources. With an AET rate of 1177.44 mm year^{-1}, it emphasises the importance of considering types of woodlands when assessing hydrology (Creed & Noordwijk, 2018). A global review study by Rahman et al. (2023) found that coniferous evergreen trees have the highest mean transpiration rate (0.7 mm day^{-1}) compared to broadleaved deciduous trees (0.5 mm day^{-1}), shrubs (0.4 mm day^{-1}) and broadleaved evergreen trees (0.2 mm

day^{-1}). This suggests that conifers can be more effective in reducing storm-water runoff due to their higher transpiration rates (Rahman et al., 2023). Breil et al. (2021) explored this question through a regional model with idealised afforestation scenarios for Europe. Forests typically have higher ET rates than grasslands in the tropics due to deeper roots, higher Leaf Area Index (LAI) and lower albedo (Breil et al., 2021). However, factors like higher surface roughness in forests can transform solar radiation into turbulent sensible heat fluxes, leading to cooler surface temperatures compared to grasslands (Breil et al., 2021). This reduced surface temperature decreases the saturation deficit between vegetation and the atmosphere, which can reduce transpiration, resulting in lower ET (Breil et al., 2021). Applying this understanding to the UKRSB, the woodland types with higher AET rates (WL4) might have characteristics that promote higher ET, such as deeper soil profiles, greater access to groundwater or more significant vegetation density. Conversely, lower AET rates in other woodlands might reflect factors like reduced surface temperature or differences in vegetation structure. Breil et al. (2021) suggests that the relationship between land cover and ET is complex and influenced by multiple factors.

The standard error values offered insights into the precision of the mean estimates, lower standard error values, such as those observed in WL3, suggest a higher precision in estimating the true mean AET rate for that woodland. Conversely, higher standard errors values, as seen in WL4, indicate a greater degree of variability in the sample data. The median values, representing the middle point of the AET rates, further complement the discussion. For instance, the median AET rates for WL1, WL2 and WL3 fall within a relatively close range, reinforcing the stability in the central tendency of the data. WL4, with a median value of 1170.97 mm year^{-1}, aligns with its higher mean AET rate, emphasising the consistency of the results (Manikandan, 2011). The standard deviation and range values provide insights into the dispersion or spread of the AET rates within each woodland (Wan et al., 2014). Larger standard deviation and ranges values, such as those observed in WL4, suggest a wider variability in AET rates, highlighting the potential influence of diverse factors on ET the in Kalahari Woodland. The 95% confidence level, incorporated into the analysis, serves as a crucial metric for evaluating the precision of the AET estimates (Hazra, 2017). The narrow Confidence Level (CL) in WL3 indicates a higher level of confidence in estimating the true mean AET rate for that woodland, while the wider CL in WL4 reflects a greater degree of uncertainty in the estimate for the Kalahari Woodland. The high AET rate in the Kalahari Woodland is in

agreement with studies by Obakeng (2007) and Robertson (2005) in the Southern Africa region (Zambia, Namibia, Botswana and Zimbabwe).

5.8 Species-Specific ET rates and their Impact on Water Balance

For the year 2022, specific species average annual AET rates were analysed. Among these findings, it was observed that the Kalahari Woodland had AET rate of 1444.6 mm year^{-1}. These particular pixels in the woodland were mainly dominated by *Julbernardia globiflora*. Additionally, Pine (*Pinus kesiya* and *Pinus oocarpa*) and Eucalyptus (*Eucalyptus grandis*) plantations exhibited the average AET rate of 1280 mm year^{-1}. Table 5.4 provides an overview of these results.

Table 5.4: Dominant species and the average annual AET rates 2022 for the selected pixels in the UKRSB, Zambia.

Variables	Pixels	Latitude	Longitude	Three Dominant Species	Characteristics	mm year^{-1} AET	mm year^{-1} Mean AET
Parinari Woodland	1	-12.686	28.47	*Parinari curatellifolia* *Isoberlinia angolensis* *Julbernardia paniculata*	Deciduous; Total Canopy Cover (TCC) 50%; Tree heights ranged between 5 m – 30 m; Soil mostly clay and silt; and DBH ranged between 5 cm – 45 cm	1242	1252.8
	2	-12.653	28.463			1243	
	3	-12.686	28.474			1246	
	4	-12.655	28.461			1261	
	5	-12.651	28.472			1272	
Miombo/Chipya Woodland	6	-13.021	28.289	*Isoberlinia angolensis* *Julbernardia paniculata* *Brachystegia boehmii*	Deciduous; TCC 50%; Tree heights ranged between 5 m – 25 m; Soil mostly silt; and DBH ranged between 5 cm – 77 cm	1236	1252.8
	7	-13.041	28.204			1248	
	8	-13.021	28.285			1253	
	9	-13.012	28.271			1257	
	10	-13.001	28.233			1270	
Munga Woodland	11	-13.425	27.912	*Acacia polyacantha* *Combretum zeyheri* *Ficus capensis*	Deciduous; TCC 50%; Tree heights ranged between 5 m – 23 m; Soil mostly clay and silt; and DBH between ranged 5 cm – 84 cm	1161	1215.8
	12	-13.443	27.942			1201	
	13	-13.45	27.943			1234	
	14	-13.452	27.943			1236	
	15	-13.45	27.945			1247	
Kalahari Woodland	16	-13.999	27.597	*Julbernardia globiflora* *Xylopia odoratissima* *Brachystegia boehmii*	Deciduous; TCC 50%; Tree heights ranged between 5 m – 25 m; Soil mostly sandy; and DBH ranged between 5 cm – 75 cm	1435	1444.6
	17	-14.001	27.613			1436	
	18	-14.001	27.61			1439	
	19	-14.004	27.608			1445	
	20	-14.004	27.611			1468	
Pine Plantation	21	-12.644	28.41	*Pinus kesiya* *Pinus oocarpa*	Evergreen conifers; TCC 75%; Tree heights ranged between 35 m – 45 m; Soil mostly clay and silt; and DBH ranged between 21 cm – 31 cm	1328	1280
	22	-12.653	28.421			1271	
	23	-12.655	28.421			1268	
	24	-12.655	28.423			1249	
	25	-12.651	28.419			1253	
Eucalyptus Plantation	26	-12.626	28.387	*Eucalyptus grandis*	Evergreen; TCC 75%; Tree heights ranged between 35 m – 55 m; Soil mostly clay and silt; and DBH ranged between 18 cm – 29 cm	1258	
	27	-12.628	28.392			1320	
	28	-12.631	28.392			1261	
	29	-12.628	28.389			1310	
	30	-12.628	28.394			1282	

Parinari Woodland, characterised by deciduous trees with a 50% density, DBH of 5 cm to 45 cm and heights ranging from 5 m to 30 m in clay and silt soils, exhibited mean AET rates ranging from 1242 mm year^{-1} to 1272 mm year^{-1} across its pixels. Species frequency is shown in figure 5.15.

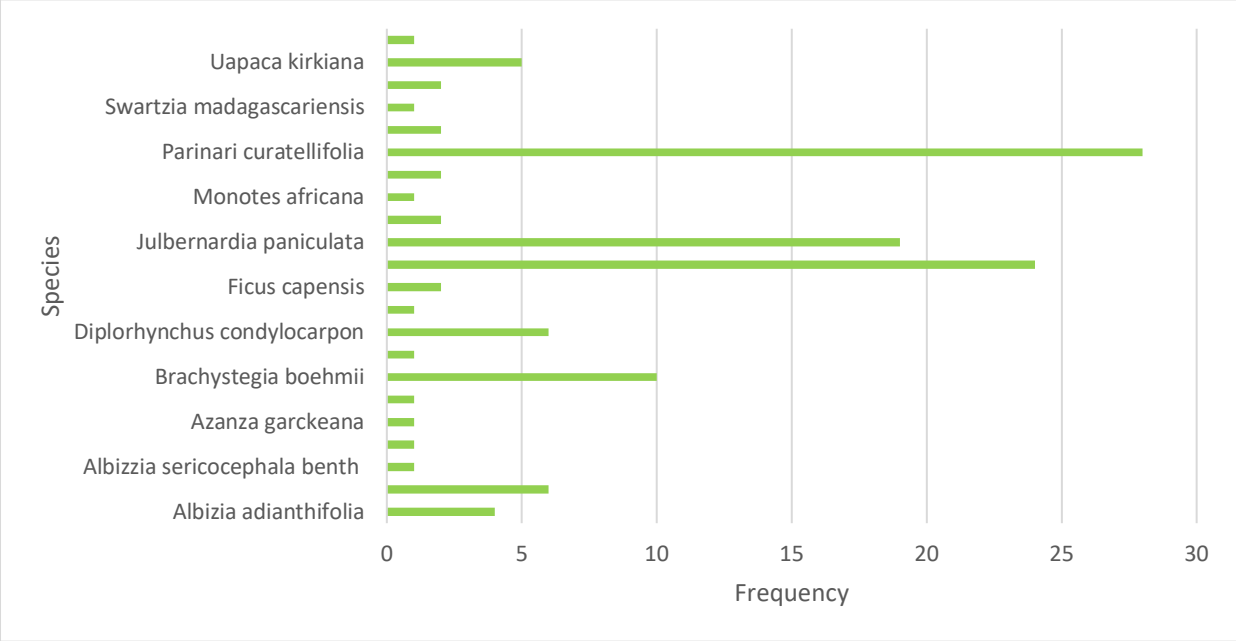

Figure 5.15: Species frequency in the Parinari Woodland of Ngala Forest, Mufulira, Zambia.

Miombo/Chipya Woodland, with similar characteristics but situated in silt soils, demonstrated mean AET rates ranging from 1236 mm year^{-1}to 1270 mm year^{-1}. Species frequency is shown in figure 5.16.

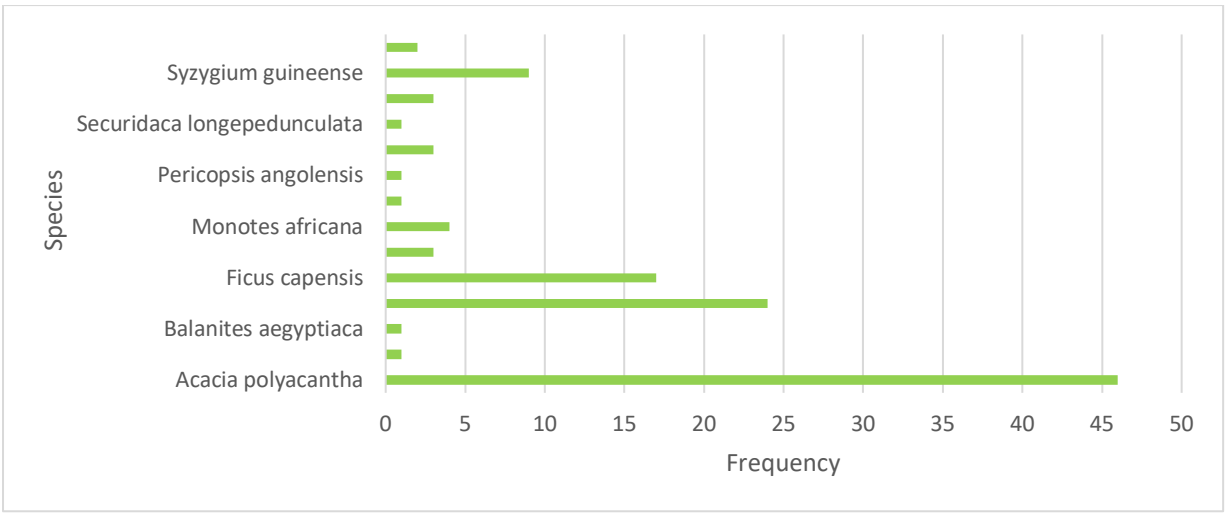

Figure 5.16: Species frequency in the Miombo/Chipya Woodland of Muva Forest, Luanshya, Zambia.

Munga Woodland, featuring deciduous trees with a 50% density, DBH of 5 cm to 84 cm and heights of 5 m to 23 m in clay and silt soils, showcased mean AET rates ranging from 1161 mm year^{-1} to 1247 mm year^{-1}. Species frequency is shown in figure 5.17.

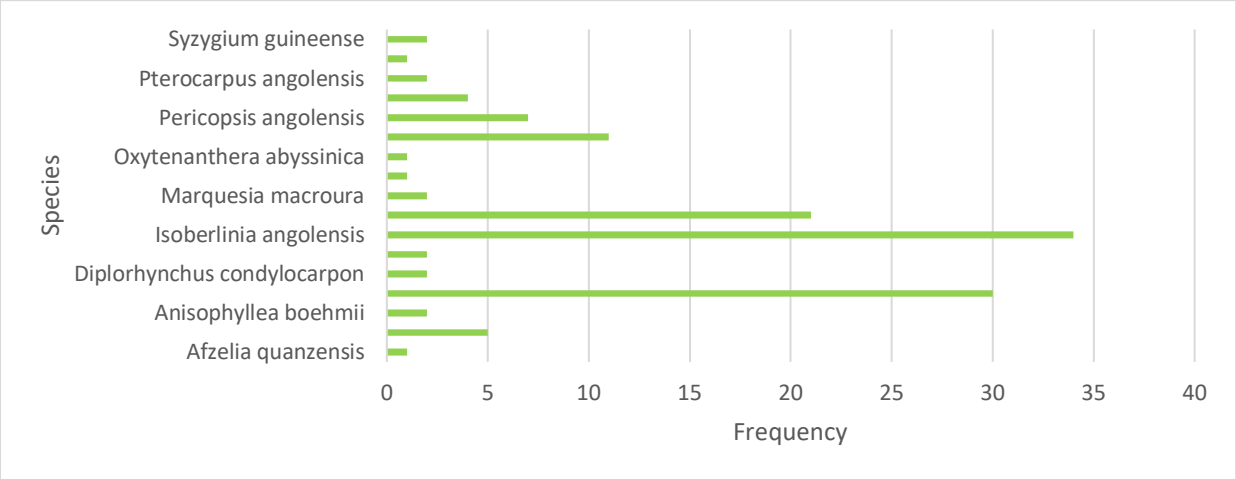

Figure 5.17: Species frequency in the Munga Woodland, Mpongwe, Zambia.

Notably, Kalahari Woodland, characterised by deciduous trees with a 50% density, DBH of 5 cm to 75 cm and heights of 5 m to 25 m in sandy soils, exhibited particularly high mean AET rates ranging from 1435 mm year^{-1}to 1468 mm year^{-1}. Species frequency is shown in figure 5.18.

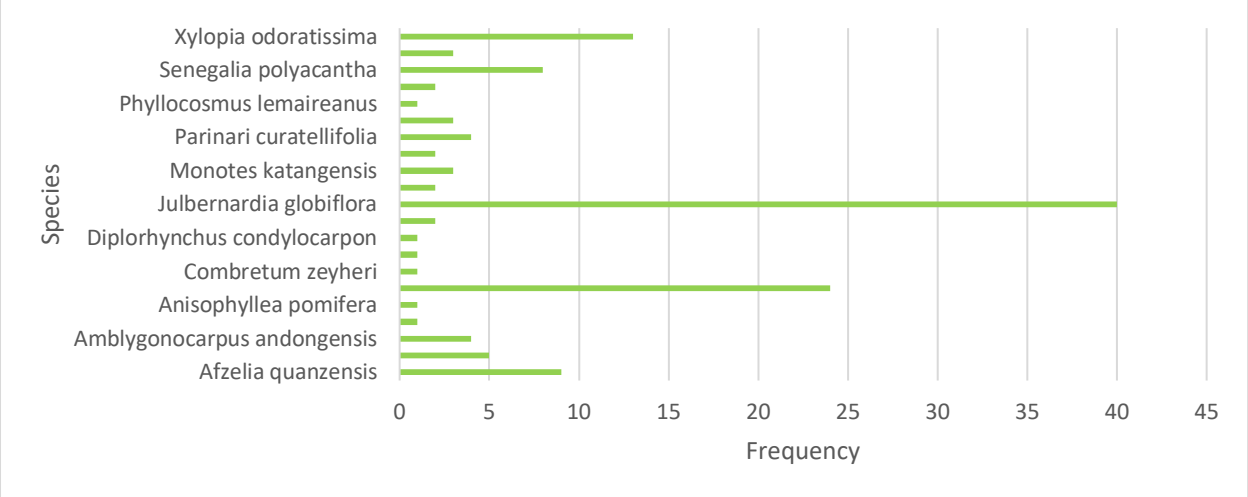

Figure 5.18: Species frequency in the Kalahari Woodland, Ngabwe, Zambia.

Additionally, Pine Plantation, comprised evergreen conifers with a 75% density and heights of 35 m to 45 m aged 25 to 30 years in clay and silt soils, demonstrated mean AET rates ranging from 1249 mm year^{-1} to 1328 mm year^{-1}. Eucalyptus plantations, featuring evergreen trees with a 75% density and heights of 35 m to 55 m aged 5 years in clay and silt soils, exhibits mean AET rates ranging from 1258 mm year^{-1} to 1320 mm year^{-1}.

The total density of the study area is 931,179,448 trees based on a density map (Figure 5.19) by Crowther (2015).

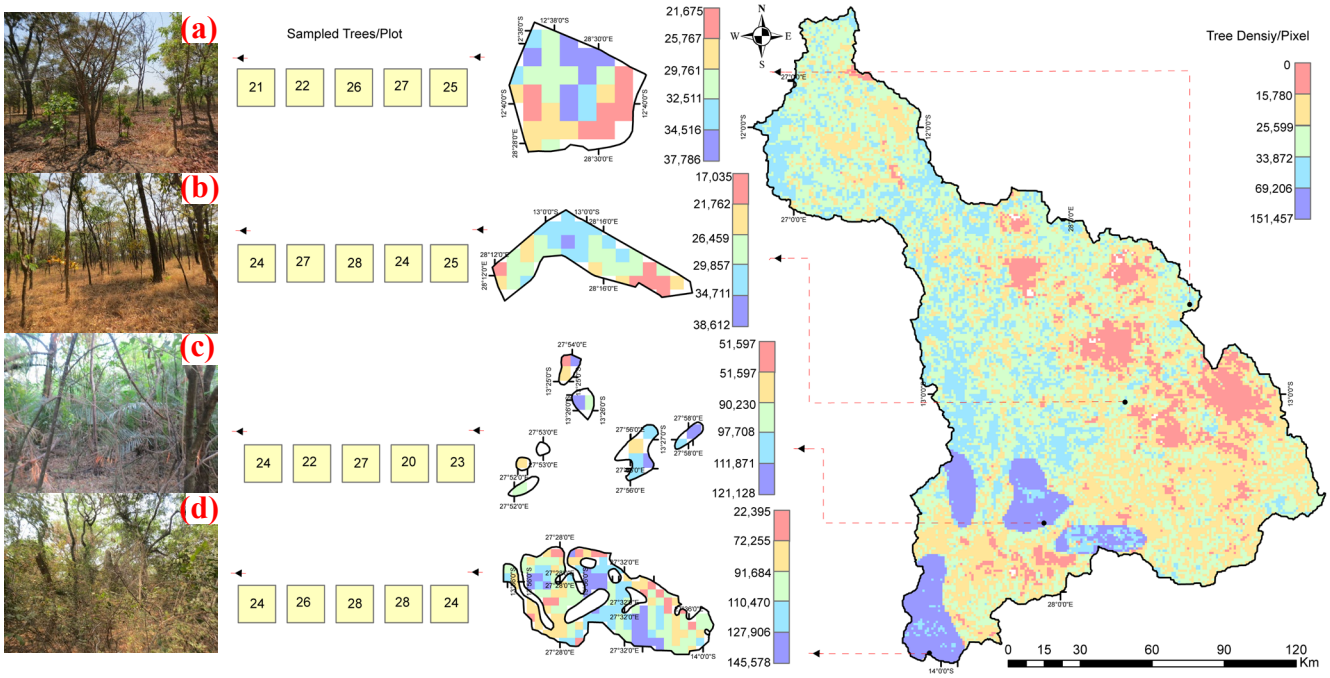

Figure 5.19: Tree density map of the UKRSB, Zambia (Crowther, 2015). a) Tree density in Ngala Forest; b) Tree density in Muva Forest; c) Tree density in Munga Woodland; and d) Tree density in kalahari Woodland.

Specifically, Parinari Woodland (Ngala Forests) with 1,078,549 trees (Figure 5.19a), Miombo/Chipya Woodland (Muva Forest) with 1,156,682 trees (Figure 5.19b), Munga Woodland with 1,413,212 trees (Figure 5.19c) and Kalahari Woodland with 17,767,525 trees (Figure 5.19d). Each 30 m x 30 m sample plot included 20 to 28 sample forest trees.

The Total Canopy Cover (TCC) (Figure 5.20) is estimated at 33.91% for the UKRSB. Specifically, Parinari Woodland (Ngala Forests) with 44.83% (Figure 5.20a), Miombo/Chipya Woodland (Muva Forest) with 40.38% (Figure 5.20b), Munga Woodland with 28.32% (Figure 5.20c) and Kalahari Woodland with 34.21% (Figure 5.20d).

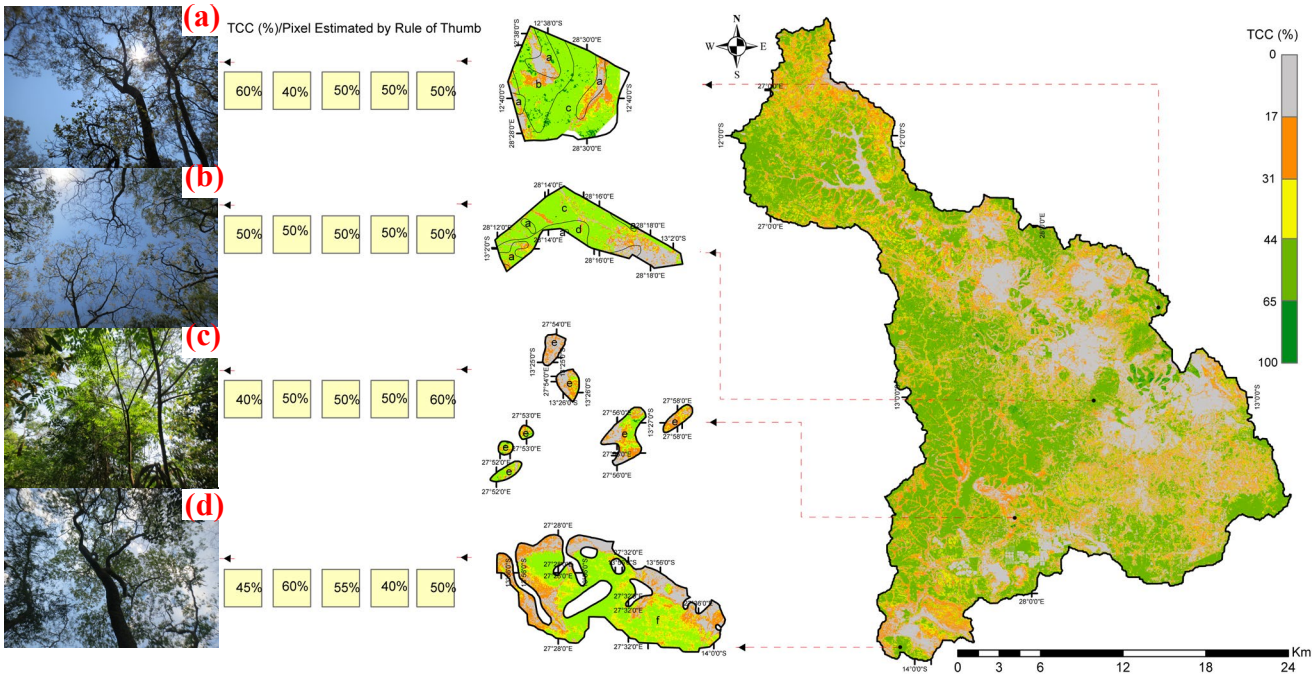

Figure 5.20: Total Canopy Cover for the UKRSB, Zambia. a) TCC in Ngala Forest; b) TCC in Muva Forest; c) TCC in Munga Woodland; and d) TCC in the Kalahari Woodland.

In the four primary woodlands identified, while all these woodlands play roles in shaping the regional water balance, it is the Kalahari Woodland that stands out due to its high ET rates. Within the Kalahari Woodland, *Julbernardia globiflora* was found to be the leading contributor to the elevated ET rates, owing to its predominance in the selected pixels. A study by Obakeng (2007) in the Kalahari Region of Botswana, investigated the characteristics of large-scale spatial and temporal variability of moistening and its effects on water resources. The research observed that while rainfall in this region is concentrated in the hot summer season, PET far exceeds the annual rainfall leading to high rates of water loss primarily through ET and minimal surface runoff. This aligns with the findings in the UKRSB, where similar high ET rates were noted, particularly in the Kalahari Woodland with mean AET rates ranging from 1435 mm year^{-1} to 1468 mm year^{-1}. Obakeng (2007) highlighted that specific tree species in the Kalahari Desert have deep root systems that allow them to extract moisture from depths of more than 70 metres, indicating that groundwater may also contribute to the high ET rates. This understanding resonates with the UKRSB findings, where elevated ET rates in Kalahari Woodland species (*Julbernardia globiflora*) and Pine/Eucalyptus plantations point to deep-rooted vegetation and groundwater extraction contributing to high ET levels. A study by Liu et al. (2017) examined Eucalyptus plantations in subtropical China revealing high ET rates with annual ET for two, four and six year old Eucalyptus plantations at 876.7 mm year^{-1}, 944.1 mm year^{-1} and 1000.7 mm year^{-1} respectively. This suggests that these plantations can substantially reduce regional water availability due to high ET (Liu et al., 2017). Similarly, in the UKRSB, Eucalyptus plantations

exhibited elevated AET rates. Ouyang et al. (2021) investigated hydrological effects of three tree plantations in South China, *Schima wallichii*, *Acacia mangium* and *Cunninghamia lanceolata* by monitoring sap flow and applying a water balance approach over two years. The study found that broadleaved plantations like *S. wallichii* and *A. mangium* exhibited higher stand-scale transpiration and ET compared to coniferous *C. lanceolata* with a higher ratio of ET to precipitation (ET/P) in broadleaved plantations exceeding 1 during the dry season indicating potential water stress on regional water resources (Ouyang et al., 2021). The findings highlight that broadleaved tree species, despite their benefits may pose a threat to a basin's water yield and balance. In the UKRSB, high ET rates in broadleaved Kalahari Woodland (*Julbernardia globiflora*) align with Ouyang et al. (2021) findings, suggesting that broadleaved species might lead to increased ET thus impacting water resource sustainability. Therefore, the need for more water to maintain these losses and other economic developments.

Several factors underpin the exceptional ET rates observed in the Kalahari Woodland. These factors include species diversity, with various tree species exhibiting differing ET behaviours (Breil et al., 2021). The presence of multiple tree species with high transpiration rates collectively elevates the woodland's ET. Moreover, the morphological and physiological attributes of tree species, including leaf size and shape, play a crucial role in enhancing transpiration (Zimba et al., 2022a; 2023). Efficient root systems maximise water uptake from the soil, contributing to increased transpiration rates (Bakhshandeh et al., 2016; Yan et al., 2022; Yang et al., 2018). Local hydrological conditions, such as groundwater availability and soil moisture, facilitate high ET rates (Obakeng, 2007). Additionally, regional climate patterns, encompassing temperature and humidity, significantly impact ET rates and the Kalahari Woodland's response to these climatic factors enhances its ET potential (Obakeng, 2007). Pine and Eucalyptus plantations are predominantly concentrated in the Copperbelt Region of Zambia. These non-native tree species exhibited also higher rates of AET. These species are conifers and as expected, exhibit higher rates (Breil et al., 2021). The contribution of vegetation types, Forests/Pine and Eucalyptus to regional water dynamics is consistent with existing literature that highlights the ecological importance of forests in regulating hydrological processes (Creed & Noordwijk, 2018), indicating the impact that certain tree species have on water dynamics (Scott & Prinsloo, 2008).

5.9 Implications for IBWT and IWRM

The results from this study have important implications for both IBWT from the LRB to the KRB and IWRM. The findings underscore the complex interplay between forest cover, ET and hydrological processes all of which play a critical role in planning and managing IBWT and IWRM strategies.

5.9.1 Relevance to IBWT

The observed ET rates in the UKRSB highlight the potential challenges of water loss due to high ET, especially in woodland ecosystems with dense vegetation like the Kalahari and Miombo/Chipya woodlands. As mentioned earlier, the high ET rates, particularly in Kalahari woodlands (mean AET of 1444.6 mm year^{-1}), indicate that forested areas significantly influence the overall water balance. This has implications for the proposed IBWT. If the IBWT is implemented, understanding these high ET rates is crucial to ensure the effective management of the transferred water. Given that water loss due to ET can significantly reduce the available water for other uses, the high rates observed in this study suggest that careful planning is needed to minimise the risk of water depletion through ET (FAO, 2019). This aligns with findings from Liu et al. (2022) and the WaSSI model, where hydrological models can help to estimate the contribution of forested river basins to surface drinking water supply and assess the potential impact of IBWT on water resources. The findings of this study indicate high AET in the KRB, resulting in reduced water resources and consequently a greater demand for water to satisfy both AET and other economic needs, thus emphasising the necessity for an IBWT.

5.9.2 IWRM and Scientometrics

The systematic literature review and bibliometric analysis conducted in this study offer valuable insights into the state of research on the forest-water nexus in Zambia. The PRISMA framework was instrumental in identifying key articles, revealing the collaboration networks among researchers in this field and suggesting areas where additional research is needed. This approach aligns with IWRM principles by providing a structured method to integrate scientific knowledge into water resources management (Gupta & van-der-Zaag, 2008).

The co-authorship network visualisation indicated strong collaboration among researchers, with central figures acting as hubs for knowledge exchange (Van-Eck & Waltman, 2010). This collaborative approach is central to IWRM, where interdisciplinary research and stakeholder engagement are key to developing sustainable water management strategies (UNEP, 2015). The network-based structure observed in the bibliometric analysis emphasises the need for integrated approaches in water resources management, promoting collaboration across various disciplines (Donthu et al., 2021). Moreover, the analysis identified areas where research is lacking or underexplored, pointing to opportunities for further investigation and the development of more robust IWRM strategies. The gaps in knowledge, especially regarding the impact of deforestation and ET rates in forested areas, suggest that more comprehensive studies are needed to inform sustainable water management practices in the KRB (FAO, 2019).

5.9.3 Implications for Water Conservation

The findings of this study have significant implications for water conservation efforts in the KRB. The high ET rates in forested areas underscore the need for targeted conservation strategies to manage water loss through ET (Creed & Noordwijk, 2018). Given the observed decline in AET over time, there is a need to assess the factors contributing to this trend and implement measures to mitigate water loss due to ET (Mwelwa, 2004). The proposed IBWT from Luapula River Basin to KRB through the ORTARChI Project is one factor that would mitigate water loss. Conservation efforts, such as reforestation, sustainable forestry practices, and protection of riparian zones, can play a crucial role in maintaining the hydrological balance and reducing water loss (Scott & Prinsloo, 2008). The observed relationship between NDVI and AET indicates that vegetation health and density are key factors in water conservation (Kasaro et al., 2019). Therefore, in addition, strategies that promote forest regeneration and sustainable land use can help to reduce ET and enhance water retention within the basin (FAO, 2015).

5.9.4 Summary

Overall, the results from this study suggest that successful IBWT and IWRM require a deep understanding of the forest-water nexus, with particular attention to factors such as ET rates and land cover. Scientometric approaches, like the systematic literature review and bibliometric analysis, provide valuable insights into the existing body of knowledge and can guide future research and policy development in water resources management. These findings underscore the need for integrated, collaborative and conservation-focused approaches to ensure sustainable water management in the KRB and beyond. IBWT is needed to mitigate water loss in the KRB due to high AET, as the water cannot be taken all at once but needs to be balanced.

CHAPTER SIX: CONCLUSION AND RECOMMENDATION

6.1 Overview

This chapter concludes the study on the forest-water nexus, offering strategic recommendations for integrated management and collaborative efforts in Zambia's KRB.

6.2 Conclusion

The systematic literature review using PRISMA identified 25 papers focused on the forest-water nexus, pointing to a limited body of research on this topic within the Zambian context. The bibliometric analysis revealed small co-author clusters with notable central figures like Paletto and Springgay, indicating a collaborative but relatively small research community. This suggests an opportunity for broader collaboration and integration of various disciplines, crucial for a comprehensive understanding of forest-water dynamics in the context of IWRM and IBWT.

Field observations highlighted the critical role of *Nymphaeaceae* (water lilies) and riparian forests in stabilising riverbanks and reducing turbidity, thus contributing to water quality. Seasonal fluctuations in these forests impact vegetation and erosion, underscoring the importance of water conservation efforts. The spatial distribution of AET in 2022 ranged from 268 mm year^{-1} to 1505 mm year^{-1}, with a mean of 985 mm year^{-1}, reflecting the influence of land cover and climatic conditions. These variations in AET underscore the need for IWRM strategies that consider seasonal and land cover factors.

The correlation between NDVI and AET reveals seasonal variability, with a moderate correlation during the dry season ($r^2 = 0.48$) and a weaker correlation in the wet season ($r^2 = 0.32$). These findings highlight the influence of vegetation greenness on AET rates, emphasising the need for targeted forest management practices that account for seasonal changes to optimize water conservation efforts in the UKRSB. The observed decline in AET from 2009 to 2022, with a statistical slope of -12.143 and a P-Value of 0.016, indicating shifts in climate, land use practices (high deforestation) and depleted water resources as PET is slowly increasing.

AET rates across different woodland types in the UKRSB demonstrated variations based on vegetation structure and composition. Kalahari Woodland (WL4) exhibited the highest AET rates (1177 mm year^{-1}), potentially due to unique ecological characteristics and access to groundwater, with pixels in 2022 showing an average of 1444.6 mm year^{-1}, mainly *Julbernardia globiflora*. Miombo/Chipya (1082 mm year^{-1}), Parinari (1005 mm year^{-1}) and Munga (1005 mm year^{-1}) woodlands showed lower rates. *Pinus kesiya* and *Eucalyptus grandis* plantations also demonstrated elevated AET rates both at 1280 mm year^{-1}.

Overall, achieving sustainable IBWT requires a comprehensive approach that integrates the forest-water nexus, collaborative research and water conservation efforts. The forest land cover of the UKRSB is a net consumer of water resources in some years. To address these aspects, IBWT projects are needed that support long-term water resource management while minimising water loss and mitigating unintended consequences. 4.37 billion m^3 is needed annually to offset water loss seasonal variations based on the established 80 mm $month^{-1}$ ET rate threshold. Parinari and Munga woodlands presents the optimal land cover for IBWT. Riparian forests should be planted along the channels of transferred water to stabilise the riverbanks. However, due to the study's delimitations further investigations should be carried for validation. Species-specific ET rates of riparian forest should be considered too. The insights from this study contribute to the broader understanding of IWRM and offer a pathway towards a more inclusive water management strategy for IBWT.

6.3 Recommendations

Given the high AET rates observed in Kalahari Woodland, pine and eucalyptus plantations, it is essential to adopt strategic forest management practices. Afforestation and reforestation efforts should prioritize alternative tree species that optimize water retention while maintaining ecological integrity. Parinari and Munga woodlands, which exhibit lower ET rates could serve as viable alternatives for conserving water in IBWT projects. Additionally, forests in general should be managed holistically integrating hydrological considerations to balance ecological sustainability and water resource conservation.

For sustainable IBWT planning, it is crucial to assess the hydrological impact of different land cover types. Water transfer schemes should prioritize areas with lower ET rates to minimize excessive water loss and enhance sustainability. Given that high ET species such as pine and eucalyptus can significantly impact water availability, future land-use strategies should focus on species diversification and adaptive management practices to optimize water conservation within forested catchments.

Integrated land-use policies should support mixed forest landscapes that balance ecosystem services, biodiversity and water availability. Sustainable forest management frameworks should incorporate guidelines for selecting tree species based on their water use efficiency. Additionally, future research should consider determining the age of trees, as age significantly influences ET rates, biomass accumulation and overall water use efficiency. Understanding these dynamics will be critical for improving forest-water management strategies.

Remote sensing techniques such as NDVI have proven useful for assessing vegetation-water interactions, but future studies should integrate both NDVI and LAI analysis for a more comprehensive understanding of canopy structure and hydrological processes. Furthermore, for ET estimation at the species level, direct measurement techniques, such as using a sap flow meter, should be considered to provide species-specific water use data. This approach would enhance accuracy in determining the water demands of individual tree species and contribute to more effective forest-water conservation strategies.

Lastly, climate resilience strategies should be integrated into forest management plans. This includes selective logging, improved catchment conservation and adaptive land-use planning to mitigate potential water stress and enhance ecosystem stability. By incorporating these measures, forest landscapes can be managed more sustainably, ensuring long-term water security in the UKRSB.

Specific to the Zambian government. The observed high ET rates in Kalahari Woodland, pine and eucalyptus plantations reinforce the need for integrated forest-water governance. The Forest Department under the Ministry of Green Economy and Environment and WARMA under the Ministry of Water Development and Sanitation should collaborate to establish a dedicated subunit group focusing on river basin management across all basins and sub-basins in Zambia. This initiative would ensure that water conservation strategies align with sustainable forestry practices, considering species-specific water demands.

The study underscores the knowledge gap in forest hydrology within academic programs in Zambia, limiting the country's ability to train professionals equipped for sustainable forest-water management. Consequently, universities particularly those offering forestry programs, such as Copperbelt University should integrate forest hydrology as a core undergraduate course. This will equip students with a deeper understanding of forest-water interactions, enabling them to contribute effectively to sustainable resource management.

The National Action Plan on carbon-centered afforestation strategies, while beneficial for carbon sequestration, presents long-term risks to water availability, particularly in areas where high-ET species dominate. The findings suggest that pine and eucalyptus plantations significantly contribute to water loss, emphasizing the need to re-evaluate the afforestation strategy to avoid unintended water scarcity issues. The Ministry of Green Economy and Environment should consider revising this strategy to prioritize alternative tree species with lower ET rates and sustainable water use.

For the ORTARChI Project, findings indicate that any IBWT initiatives in the KRB must account for potential water losses due to high-ET tree species and other hydrological impacts. Managing these risks requires a multidisciplinary approach, involving hydrologists, hydrogeologists, foresters, soil scientists and climate experts. Furthermore, the eWEF model as referenced in the study can serve as a valuable tool for evaluating the long-term sustainability of large-scale engineering interventions ensuring that IBWT strategies support rather than deplete water resources.

The study highlights gaps in species-specific ET estimation, particularly the need for direct measurement techniques to improve accuracy. To advance research in this area, the Ministry of Technology and Science should prioritize research on the forest-water nexus, including species-specific ET models, geographic expansion, long-term monitoring sites and climate change projections. Sap flow meters should be adopted for ET estimation of individual species, providing precise data to guide afforestation and reforestation policies.

Finally, findings reinforce the importance of collaborative knowledge exchange among key stakeholders. The Government of the Republic of Zambia should continue capacity-building efforts, fostering collaboration among researchers, practitioners, policymakers and local communities. Strengthening partnerships between the Forest Department, WARMA, universities and research institutions will enhance sustainable resource management and ensure the long-term conservation of Zambia's water and forest ecosystems.

By integrating these recommendations, decision-makers can ensure that forest and water resource management strategies are scientifically grounded, ecologically sustainable and economically viable for future generations.

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APPENDICES

Appendix 1: Field Observation Sheet for the UKRSB, Zambia, Forest-Water Nexus Study adapted from FAO (2015).

FIELD OBSERVATION SHEET

This field observation sheet is designed to record aspects of the forest-water nexus in the UKRSB. By documenting forest characteristics, water resources, flora and fauna, human activities and ecosystem services, its aimed to gain insights into the relationships shaping this ecosystem.

Instructions:

- Please fill out the relevant sections below based on direct observations during the field survey.
- Be as detailed and accurate as possible, ensuring consistency in recording observations.
- Use additional space for any additional notes or observations not covered by the checklist.

1. General Information	
Observers Name:	
Date of Observation:	
Location:	
Weather:	
Time of Day:	
2. Forest Characteristics	
• Type of forest (e.g., tropical rainforest, deciduous forest, etc.)	
• Canopy coverage (%)	
• Species diversity	
• Presence of invasive species	
3. Water Resources	
• Type of water bodies (e.g., river, stream, lake, wetland)	
• Water quality indicators (e.g., turbidity)	
• Presence of pollution sources (if any)	
4. Human Activities	
• Agriculture (e.g., farming, grazing)	
• Logging and forestry activities	
• Mining activities	
5. Ecosystem Services	
• Water provisioning	
• Biodiversity conservation	
• Carbon sequestration	

Appendix 1 cont…

Field Notes

Capture qualitative observations that may not fit neatly into a checklist format.

Dry Season Notes

- Clear sky day, providing optimal conditions for observation.
- General health of the forest: Overall, the forest appears to be in good health, with a diverse range of tree species and signs of degradation or deforestation. Canopy coverage is estimated to be around 70%, providing ample shade and habitat for various fauna and flora.
- Water lilies observed on streams: During the survey, numerous water lilies were observed along the streams within the forest. Notable observation of clear water in streams where water lilies were present, suggesting a potential role of these plants in influencing water turbidity. This observation warrants further investigation into the mechanisms through which water lilies affect water clarity in the ecosystem.
- Riparian forests: The riparian forests along the riverbanks exhibit dense vegetation, primarily comprised of trees with extensive root systems. Riparian forests along the banks of the Kafue River in Luanshya and Ngabwe demonstrated their importance in stabilizing riverbanks and mitigating erosion.
- Biodiversity: The forest supports a rich diversity of flora and fauna, including various species of birds, mammals and insects. During the survey, very little biodiversity was observed. A few bird species were observed indicating the importance of the forest as a habitat and breeding ground for wildlife.
- Human activities: Signs of human activities such as agriculture and logging were minimal within the core forest areas, evidence of encroachment and small-scale farming was observed along the forest edges. These activities pose a potential threat to the integrity of the forest ecosystem and highlight the need for sustainable land management practices.
- Lake Kashiba in Mpongwe is known to be mystical lake locally and worldwide. Its water level seemed Stable and it is surrounded by a dense vegetation.
- Carbon sequestration: The dense vegetation and extensive tree cover in the forest facilitate carbon sequestration, helping to mitigate climate change by capturing and storing carbon dioxide from the atmosphere. The presence of old-growth trees and mature forests further enhances the carbon sequestration potential of the ecosystem.

Wet Season Notes

- Most days were characterized by cloudy weather conditions, typical of the wet season, Dangerous for Conducting research.
- Increased vegetation growth observed across all woodland types, contributing to expanded canopy coverage and denser foliage.
- Enhanced species diversity noted, with a proliferation of herbaceous plants and shrubs complementing the existing tree canopy.
- No change observed in the presence of invasive species.
- Significant increase in water bodies observed, with seasonal streams rejuvenated and flowing.

Appendix 2: PRISMA 2020 Checklist (Page et al., 2021).

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g., for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	
	10b	List and define all other variables for which data were sought (e.g., participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	
Effect measures	12	Specify for each outcome the effect measure(s) (e.g., risk ratio, mean difference) used in the synthesis or presentation of results.	
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g., tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	
	13d	Describe any methods used to synthesise results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g., subgroup analysis, meta-regression).	
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesised results.	
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	

Appendix 2 cont…

Section and Topic	Item #	Checklist item	Location where item is reported
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	
Study characteristics	17	Cite each included study and present its characteristics.	
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g., confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesised results.	
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	
	23b	Discuss any limitations of the evidence included in the review.	
	23c	Discuss any limitations of the review processes used.	
	23d	Discuss implications of the results for practice, policy, and future research.	
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	
Competing interests	26	Declare any competing interests of review authors.	
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	

Appendix 3: Google Earth Engine script used for cumulative NDVI computation for in the UKRSB, Zambia for the year 2022.

```
var studyArea = ee.FeatureCollection(polygon)

Map.addLayer(studyArea, {}, 'My polygon')
// Define the date range for 2022.
var startDate = '2022-01-01';
var endDate = '2022-12-31';

// Load the Sentinel-2 image collection.
var sentinel2 = ee.ImageCollection('COPERNICUS/S2')
  .filterBounds(studyArea)
  .filterDate(startDate, endDate)
  .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 10))
  .select(['B4', 'B8']); // Select Red (B4) and NIR (B8) bands.

// Function to calculate NDVI.
var calculateNDVI = function(image) {
  var ndvi = image.normalizedDifference(['B8', 'B4']).rename('NDVI');
  return image.addBands(ndvi);
};

// Apply the NDVI calculation to each image.
var ndviCollection = sentinel2.map(calculateNDVI);

// Reduce the collection to a single image by taking the median.
var ndviComposite = ndviCollection.select('NDVI').median().clip(studyArea);

// Define visualization parameters.
var ndviVis = {
  min: -1,
  max: 1,
  palette: ['red', 'yellow', 'green']
};

// Display the NDVI composite on the map.
Map.centerObject(studyArea, 8);
Map.addLayer(ndviComposite, ndviVis, 'NDVI Composite');
// Export the NDVI composite as a GeoTIFF.
Export.image.toDrive({
  image: ndviComposite,
  description: 'UKRSB_NDVI_2022',
  folder: 'EarthEngineImages',
  fileNamePrefix: 'UKRSB_NDVI_2022',
  region: studyArea,
  scale: 30,
  crs: 'EPSG:4326',
  maxPixels: 1e13
});
```

Appendix 4: Forest inventory data collected (Dry season: 22nd to 30th September, 2022, Wet season: 6th to 14th April, 2023 and 03rd to 23rd May2023) in Ngala Forest Reserve, Mufulira, Zambia.

Parinari Woodland						
Plot 1 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Brachystegia boehmii	Umusamba	22.28	17.59	Broad	Bark rough with transverse cracks, source of fibre and timber	Clay, Silt
Brachystegia boehmii	Umusamba	55.7	24.7	Broad	Bark rough with transverse cracks, source of fibre and timber	
Uapaca kirkiana	Masuku	14.96	12.09	Broad	Bears editable fruits	
Uapaca kirkiana	Masuku	27.37	19.2	Broad	Bears editable fruits	
Albizzia sericocephala benth	Umusase	20.1	17.2	Broad	Local use as a medicine, source of wood and other materials	
Julbernardia paniculata	Umutondo	27.37	19.2	Broad	Bark on bole flaking in roughly square scales	
Swartzia madagascariensis	Indele	15.91	13.2	Broad	Bark dark grey rough and fissured	
Uapaca sansibarica	Umusukolobe	20.69	17.3	Broad	Fruit fleshy spherical, yellow when ripe	
Syzygium cordatum	Umusafwa	5.77	3.59	Broad	Bears editable fruits: purple/black when ripe	
Syzygium cordatum	Umusafwa	5.77	17.79	Broad	Bears editable fruits: purple/black when ripe	
Anisophyllea boehmii	Umufungo	5.78	3.65	Broad	Bears editable fruits	
Parinari curatellifolia	Impundu	25.56	18.7	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	24.3	20	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	25.3	20.4	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	19.3	15	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	13.4	14.89	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	28.3	20	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	25.2	21.2	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	22	22.24	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	20.27	21.2	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	19.23	14.3	Broad	Bears editable fruits: Medicinal: agroforestry	

Appendix 4 cont…

Plot 2 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Diplorhynchus condylocarpon	Umwenge	7.95	6.59	Broad	Rough bark	Clay, Silt
Diplorhynchus condylocarpon	Umwenge	33.1	20.3	Broad	rough bark	
Diplorhynchus condylocarpon	Umwenge	9.23	7.2	Broad	Rough bark	
Isoberlinia angolensis	Umutobo	22.28	13.09	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	19.1	12.59	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	12.73	7	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	28.97	14.59	Broad	Medicinal and source of wood	
Brachystegia boehmii	Umusamba	7.32	2.5	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	8.28	3	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	22.28	14.59	Broad	Source of fibre and timber	
Julbernardia paniculata	Umutondo	61.11	20.59	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Umutondo	9.23	6.59	Broad	Bark on bole flaking in roughly square scales	
Albizia antunesiana	Umusase	25.15	15.68	Broad	Medicinal	
Albizia antunesiana	Umusase	27.37	17.59	Broad	Medicinal	
Albizia antunesiana	Umusase	36.29	20.4	Broad	Medicinal	
Isoberlinia angolensis	Umutombo	24	16.3	Broad	Medicinal and source of wood	
Uapaca kirkiana	Umusuku	6.05	3	Broad	Bears editable fruits	
Albizia adianthifolia	Akapetansefu	7	3	Broad	Medicinal	
Albizia adianthifolia	Akapetansefu	17.19	7.2	Broad	Medicinal	
Julbernardia paniculata	Umutondo	14	5	Broad	bark on bole flaking in roughly square scales	
Monotes katangensis	Chimpapa	31.83	12	Broad	Medicinal: Used to heal wounds	
Lannea discolor	Nakaumbu	23.55	14	Broad	Bears editable fruits: source of wood	

Appendix 4 cont…

Plot 3 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Parinari curatellifolia	Impundu	36.92	21.59	Broad	Bears editable fruits: Medicinal: agroforestry	Clay, silt
Parinari curatellifolia	Impundu	33.63	23.23	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	30.23	20.35	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	28.36	21.3	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	30.35	21.57	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	37.1	24.79	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Impundu	27.6	19.0	Broad	Bears editable fruits: Medicinal: agroforestry	
Uapaca kirkiana	Umusuku	10.18	2.5	Broad	Bears editable fruits	
Ficus capensis	Umukunyu	52.84	26.59	Broad	Rough bark, editable fruits, medicinal, shade tree	
Julbernardia paniculata	Mutondo	16	5.4	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	41	24.59	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	6	2	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	44. 75	24	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	37.3	20	Broad	Bark on bole flaking in roughly square scales	
Isoberlinia angolensis	Umutobo	40.2	21.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	43	25.3	Broad	Medicinal and source of wood	
Julbernardia paniculata	Mutondo	29.77	24.1	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	17	16.32	Broad	Bark on bole flaking in roughly square scales	
Isoberlinia angolensis	Umutobo	17	15.32	Broad	Medicinal and source of wood	
Julbernardia paniculata	Mutondo	15.3	17	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	20.5	17	Broad	Bark on bole flaking in roughly square scales	
Isoberlinia angolensis	Umutobo	43.2	27.1	Broad	Medicinal and source of wood	
Julbernardia paniculata	Mutondo	37.47	26.23	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	35.2	23.4	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	30.45	24.2	Broad	Bark on bole flaking in roughly square scales	
Julbernardia paniculata	Mutondo	17.37	17.34	Broad	Bark on bole flaking in roughly square scales	

Appendix 4 cont…

Plot 4 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/characteristics/Uses**	**Soil Profile at 10cm**
Brachystegia boehmii	Umusamba	37.24	30.59	Broad	Source of fibre and timber	Clay, Silt
Brachystegia boehmii	Umusamba	38.8	29	Broad	Source of fibre and timber	
Pericopsis angolensis	Mubanga	31.19	29	Broad	Collected for poles, firewood and medicinal purposes	
Pericopsis angolensis	Mubanga	28.6	29	Broad	Collected for poles, firewood and medicinal purposes	
Parinari curatellifolia	Mpundu	34.06	29	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	44.56	30.7	Broad	Bears editable fruits: Medicinal: agroforestry	
Erythrina abyssinica	Umulunguti	11.46	11	Broad	Medicinal, wood and fuel	
Azanza garckeana	Umukole	19.73	20	Broad	Cracked bark, Edible fruits, shade tree, produce quality ropes	
Balanites aegyptiaca	Mubambangoma	36.29	30.6	Broad	Edible fruits, medicinal	
Combretum molle	Umulama	36.6	20	Broad	Medicinal	
Monotes africana	Imchenja	36	30.59	Broad	Local use of its wood	
Ficus capensis	Umupunyu	28	10	Broad	Rough bark, editable fruits, medicinal, shade tree	
Parinari curatellifolia	Mpundu	24.42	12	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	45	25.2	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	32.2	14.48	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	46.21	29.4	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	20.34	14.92	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	31.04	24.1	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	24.79	16	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	33.46	23.37	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mpundu	35	28.4	Broad	Bears editable fruits: Medicinal: agroforestry	
Isoberlinia angolensis	Umutobo	32	28	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	29.19	27.1	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	30.3	21.34	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	33.47	25.34	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	27.35	15.69	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	31.54	25.3	Broad	Medicinal and source of wood	

Appendix 4 cont…

Plot 5 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Diplorhynchus condylocarpon	Umwenge	7.95	6.59	Broad	Rough bark, timber, latex, fibre and medicinal virtues	
Diplorhynchus condylocarpon	Umwenge	33.1	21.59	Broad	Rough bark, timber, latex, fibre and medicinal virtues	
Diplorhynchus condylocarpon	Umwenge	9.23	6.2	Broad	Rough bark, timber, latex, fibre and medicinal virtues	
Isoberlinia angolensis	Umutobo	22.28	13.09	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	19.1	12.59	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	12.73	7	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	28.97	14.59	Broad	Medicinal and source of wood	
Brachystegia boehmii	Umusamba	7.32	2.5	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	8.28	3	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	22.28	14.59	Broad	Source of fibre and timber	
Julbernardia paniculata	Umutondo	61.11	20.59	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	56.23	20.59	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Albizia antunesiana	Umusase	25.15	15.68	Broad	Local use as a source of medicines, food, wood and tannins	Clay, Silt
Albizia antunesiana	Umusase	27.37	17.59	Broad	Local use as a source of medicines, food, wood and tannins	
Albizia antunesiana	Umusase	36.29	20.4	Broad	Local use as a source of medicines, food, wood and tannins	
Isoberlinia angolensis	Umutobo	20.1	15.89	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	19.8	14.02	Broad	Medicinal and source of wood	
Uapaca kirkiana	Umusuku	6.05	3	Broad	Bears editable fruits	
Albizia adianthifolia	Akapetansefu	7	3	Broad	Bears editable fruits and medicinal purpose	
Albizia adianthifolia	Akapetansefu	17.19	7.2	Broad	Bears editable fruits and medicinal purpose	
Isoberlinia angolensis	Umutobo	14	16	Broad	Medicinal and source of wood	
Monotes katangensis	Chimpapa	31.83	12	Broad	Used to heal wounds	
Lannea discolor	Nakaumbu	23.55	14	Broad	Bears editable fruits: source of wood	
Isoberlinia angolensis	Umutobo	35.67	17.32	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	36.56	20.78	Broad	Medicinal and source of wood	

Appendix 5: Forest inventory data collected (Dry season: 22nd to 30th September, 2022, Wet season: 6th to 14th April, 2023 and 03rd to 23rd May2023) in Muva Forest Reserve, Luanshya, Zambia.

Miombo and Chipya Woodland						
Plot 1 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Brachystegia boehmii	Musamba	36.28	11.59	Broad	Source of fibre and timber	Silt
Brachystegia boehmii	Musamba	36.29	15.59	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	21.64	23.59	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	31.19	21.59	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	25.15	18.57	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	19.1	18.56	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	39.47	21.59	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	24.51	23.8	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	35.96	23.5	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	35.01	22	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	18.46	17	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	16.55	15	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	28.65	16.6	Broad	Source of fibre and timber	
Isoberlinia angolensis	Umutobo	33.26	18.59	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	37.56	21.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	7.8	8	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	29.92	11.59	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	77.03	29.59	Broad	Medicinal and source of wood	
Parinari curatellifolia	Umupundu	21.96	12.59	Broad	Bears editable fruits: Medicinal: agroforestry	
Pericopsis angolensis	Mubanga	23.24	12	Broad	Collected for poles, firewood and medicinal purposes	
Pericopsis angolensis	Mubanga	7	3	Broad	Collected for poles, firewood and medicinal purposes	
Albizia antunesiana	Umusase	10.5	16.6	Broad	Local use as a source of medicines, food, wood and tannins	
Albizia antunesiana	Umusase	21.48	15.59	Broad	Local use as a source of medicines, food, wood and tannins	
Pseudolachnostylis maprouneifolia	Umusolo	11.46	8	Broad	Medicinal, food and source of wood	

Appendix 5 cont…

Plot 2 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Julbernardia paniculata	Umutondo	28.65	26.6	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	23.55	23	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	20.7	23	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	33.42	24.6	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	33.42	21.59	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	17.19	15.6	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	17.19	15.6	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	28.97	21.59	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	19.42	19	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	25.46	22	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	31.83	21.6	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	31.83	21.6	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	17.19	23	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Brachystegia boehmii	Umusamba	19.1	24.6	Broad	Source of fibre and timber	Silt
Brachystegia boehmii	Umusamba	24.51	23.6	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	24.5	25.6	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	35.65	24.6	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	28.65	25	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	14.64	15.4	Broad	Source of fibre and timber	
Pericopsis angolensis	Mubanga	17.83	15.59	Broad	Collected for poles, firewood and medicinal purposes	
Pericopsis angolensis	Mubanga	36.61	22.6	Broad	Collected for poles, firewood and medicinal purposes	
Isoberlinia angolensis	Umutobo	17.5	15.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	21.33	18.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	5.35	2.9	Broad	Medicinal and source of wood	
Parinari curatellifolia	Umpundu	25.46	21	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Umpundu	14.64	15	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Umpundu	27.7	23.6	Broad	Bears editable fruits: Medicinal: agroforestry	

Appendix 5 cont…

Plot 3 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Anisophyllea boehmii	Umufungo	15.92	15.5	Broad	Edible fruit and useful wood	Silt
Anisophyllea boehmii	Umufungo	5	2	Broad	Edible fruit and useful wood	
Diplorhynchus condylocarpon	Mwenge	6.5	3	Broad	Rough bark, timber, latex, fibre and medicinal virtues	
Albizia antunesiana	Umusase	21	15.6	Broad	Local use as a source of medicines, food, wood and tannins	
Albizia antunesiana	Umusase	21	15.6	Broad	Local use as a source of medicines, food, wood and tannins	
Albizia antunesiana	Umusase	38.83	23.55	Broad	Local use as a source of medicines, food, wood and tannins	
Swartzia madagascariensis	Indale	7.32	3.2	Broad	Bark dark grey rough and fissured, multi-purpose wood use	
Oxytenanthera abyssinica	Bamboos	5.5	10	Broad	Edible and medicinal	
Pseudolachnostylis maprouneifolia	Umusolo	9.23	2.5	Broad	Medicinal, food and source of wood	
Monotes katangensis	Chimpapa	22.28	20.6	Broad	Used to heal wounds	
Hymenocardia acida	Akampepe	10	6	Broad	Medicinal, food and source of wood	
Hymenocardia acida	Akampepe	7.6	3	Broad	Medicinal, food and source of wood	
Julbernardia paniculata	Umutondo	16.87	20.59	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Pterocarpus angolensis	Umulombwa	15.92	16.7	Broad	Collected for poles, firewood and medicinal purposes	
Pterocarpus angolensis	Umulombwa	11.46	8	Broad	Collected for poles, firewood and medicinal purposes	
Pseudolachnostylis maprouneifolia	Umusolo	5.14	2	Broad	Medicinal, food and source of wood	
Syzygium guineense	Umufinsa	31.83	11.6	Broad	Medicinal, food and source of wood	
Syzygium guineense	Umufinsa	10.5	4	Broad	Medicinal, food and source of wood	
Isoberlinia angolensis	Umutobo	22	17.9	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	23.1	19	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	15.2	10.2	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	19.3	19	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	26.2	20.2	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	21.2	20.98	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	17.4	14.3	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	22.2	23.1	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	12	9.2	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	13	8.9	Broad	Medicinal and source of wood	

Appendix 5 cont…

Plot 4 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Afzelia quanzensis	Umupapa	5.09	4.2	Broad	Medicinal, food and source of wood	Silt
Julbernardia paniculata	Umutondo	10	12.5	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	13.37	21.6	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Brachystegia boehmii	Umusamba	14.32	20.6	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	17.19	22	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	21.33	22	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	26.41	22.5	Broad	Source of fibre and timber	
Marquesia macroura	Umufuka	16.55	16.5	Broad	Source wood for good quality charcoal	
Marquesia macroura	Umufuka	30.24	23	Broad	Source wood for good quality charcoal	
Parinari curatellifolia	Umupundu	19.42	18.59	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Umupundu	13.37	6	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Umupundu	19.1	19.59	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Umupundu	9.55	12	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Umupundu	35.01	22.6	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Umupundu	51.57	23	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Umupundu	20.7	17.89	Broad	Bears editable fruits: Medicinal: agroforestry	
Isoberlinia angolensis	Umutobo	16.87	21.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	29.28	22.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	23.24	21	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	39.5	23	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	56.66	25.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	14	17	Broad	Medicinal and source of wood	
Diplorhynchus condylocarpon	Mwenge	10.5	16.6	Broad	Rough bark, timber, latex, fibre and medicinal virtues	
Pericopsis angolensis	Mubanga	11	22	Broad	Collected for poles, firewood and medicinal purposes	

Appendix 5 cont…

Plot 5 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Brachystegia boehmii	Umusamba	38.2	26.6	Broad	Source of fibre and timber	Silt
Brachystegia boehmii	Umusamba	26.42	20.6	Broad	Source of fibre and timber	
Pericopsis angolensis	Mubanga	11	12	Broad	Collected for poles, firewood and medicinal purposes	
Brachystegia boehmii	Umusamba	40.42	22.5	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	30.56	23	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	41.38	22	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	31.83	20	Broad	Source of fibre and timber	
Brachystegia boehmii	Umusamba	20.7	12	Broad	Source of fibre and timber	
Isoberlinia angolensis	Umutobo	43.3	19.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	52.52	23.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	47.75	20.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	44.56	20	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	20.4	12	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	6	3	Broad	Medicinal and source of wood	
Pseudolachnostylis maprouneifolia	Umusolo	23.87	15.6	Broad	Medicinal, food and source of wood	
Julbernardia paniculata	Umutondo	11	12	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	47.75	21	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	40.74	20	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	76.4	23	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Julbernardia paniculata	Umutondo	10	10.7	Broad	Bark on bole flaking in roughly square scales, source of fibre	
Isoberlinia angolensis	Umutobo	51.25	20.6	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	18.46	11	Broad	Medicinal and source of wood	
Pericopsis angolensis	Mubanga	41.38	20	Broad	Collected for poles, firewood and medicinal purposes	
Isoberlinia angolensis	Umutobo	35.01	19	Broad	Medicinal and source of wood	
Isoberlinia angolensis	Umutobo	38.2	19	Broad	Medicinal and source of wood	

Appendix 6: Forest inventory data collected (Dry season: 22nd to 30th September, 2022, Wet season: 6th to 14th April, 2023 and 03rd to 23rd May2023) in Munga Woodland, Mpongwe, Zambia.

Munga Woodland						
Plot 1 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Acacia polyacantha	Munganushi	50.93	21.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	Clay, Silt
Ficus capensis	Mukuyu	39.15	18	Broad	Rough bark, editable fruits, medicinal, shade tree	
Ficus capensis	Mukuyu	67.8	23	Broad	Rough bark, editable fruits, medicinal, shade tree	
Syzygium guineense	Imifinsa	59.52	22	Broad	Medicinal, food and source of wood	
Acacia polyacantha	Munganushi	42	22	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	22	12	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	18.46	15.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	35	12.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Combretum zeyheri	Mukenge	62.7	26.6	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	48.38	24.5	Broad	Source of food, medicine and material for making baskets	
Acacia polyacantha	Munganushi	46.47	23	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	84.35	20.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Sterculia quinquelobia	Mwemwe	5.14	2	Broad	Medicinal, food and source of wood	
Syzygium guineense	Imifinsa	6.07	4.8	Broad	Medicinal, food and source of wood	
Sterculia quinquelobia	Mwemwe	20.4	18.5	Broad	Medicinal, food and source of wood	
Ficus capensis	Mukuyo	37.9	20.5	Broad	Rough bark, editable fruits, medicinal, shade tree	
Marquesia macroura	Museshi	56.02	19.56	Broad	Source wood for good quality charcoal	
Marquesia macroura	Museshi	47	20.5	Broad	Source wood for good quality charcoal	
Monotes africana	Umuchenja	25.37	23.34	Broad	Local use of its wood	
Ficus capensis	Mukuyo	12.3	6.8	Broad	Rough bark, editable fruits, medicinal, shade tree	
Ficus capensis	Mukuyo	20.4	20.4	Broad	Rough bark, editable fruits, medicinal, shade tree	
Combretum zeyheri	Mukenge	20.6	19.4	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	19.47	15.23	Broad	Source of food, medicine and material for making baskets	
Sterculia quinquelobia	Mwemwe	20.5	16.98	Broad	Medicinal, food and source of wood	

Appendix 6 cont…

Plot 2 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Acacia polyacantha	Munganushi	26.1	22.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	Clay, Silt
Acacia polyacantha	Munganushi	40.11	22.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Oldfieldia dactylophylla	Muonga	79.58	23	Broad	Medicinal, source of wood and food	
Acacia polyacantha	Munganushi	79.67	22	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Rauvolfia caffra	Mubimbi	79.58	23.6	Broad	Medicinal, source of wood and food. Agroforestry purposes	
Acacia polyacantha	Munganushi	27.7	65	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Ficus capensis	Mukuyo	20.4	20.4	Broad	Rough bark, editable fruits, medicinal, shade tree	
Combretum zeyheri	Mukenge	19.07	10.76	Broad	Source of food, medicine and material for making baskets	
Marquesia macroura	Museshi	47	20.5	Broad	Source wood for good quality charcoal	
Monotes africana	Umuchenja	50.1	20.65	Broad	Local use of its wood	
Monotes africana	Umuchenja	25.37	23.34	Broad	Local use of its wood	
Acacia polyacantha	Munganushi	26.15	22.26	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	37.11	18.36	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	22.98	22.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	40.11	20.78	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	21.9	22.68	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	40.11	21.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Combretum zeyheri	Mukenge	30.45	22.78	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	20.24	17.30	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	38.76	19.76	Broad	Source of food, medicine and material for making baskets	
Ficus capensis	Mukuyo	20.4	20.4	Broad	Rough bark, editable fruits, medicinal, shade tree	
Ficus capensis	Mukuyo	20.4	20.4	Broad	Rough bark, editable fruits, medicinal, shade tree	

Appendix 6 cont…

Plot 3 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Ficus capensis	Mukuyu	17.68	12.78	Broad	Rough bark, editable fruits, medicinal, shade tree	Clay, Silt
Monotes africana	Muchenja	12.8	6.9	Broad	Local use of its wood	
Rauvolfia caffra	Mubimbi	20.6	23.5	Broad	Medicinal, source of wood and food. Agroforestry purposes	
Combretum zeyheri	Mukenge	27.24	12.30	Broad	Source of food, medicine and material for making baskets	
Acacia polyacantha	Munganushi	20.14	12.26	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Afzelia quanzensis	Mupapa	13.76	13.8	Broad	Medicinal, food and source of wood	
Acacia polyacantha	Munganushi	21.78	12.26	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Syzygium guineense	Umufinsa	38.87	19.87	Broad	Medicinal, food and source of wood	
Balanites aegyptiaca	Mubangangoma	24.72	17.42	Broad	Edible fruits, medicinal	
Syzygium guineense	Umusombo	13.9	13	Broad	Medicinal, food and source of wood	
Acacia polyacantha	Munganushi	22.7	21	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	12.9	9.3	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	20.3	23.16	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Pericopsis angolensis	Umubanga	16.23	11.83	Broad	Collected for poles, firewood and medicinal purposes	
Acacia polyacantha	Munganushi	21.10	16.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	21.3	17.36	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	20.15	17.2	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Ficus capensis	Mukuyu	23.5	22.5	Broad	Rough bark, editable fruits, medicinal, shade tree	
Ficus capensis	Mukuyu	33.5	21	Broad	Rough bark, editable fruits, medicinal, shade tree	
Acacia polyacantha	Munganushi	22.1	22.26	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Combretum zeyheri	Mukenge	24.4	19.5	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	20.5	19.45	Broad	Source of food, medicine and material for making baskets	
Acacia polyacantha	Munganushi	21.7	21.3	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Combretum zeyheri	Mukenge	27.4	19.4	Broad	Source of food, medicine and material for making baskets	
Ficus capensis	Mukuyu	35.46	25.3	Broad	Rough bark, editable fruits, medicinal, shade tree	
Combretum zeyheri	Mukenge	29.4	17.5	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	25.74	17.60	Broad	Source of food, medicine and material for making baskets	

Appendix 6 cont…

Plot 4 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Acacia polyacantha	Munganushi	15.92	3.5	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	Clay, Silt
Combretum zeyheri	Mukenge	20.2	17.3	Broad	Source of food, medicine and material for making baskets	
Securidaca longepedunculata	Mufufuma	5.3	3.5	Broad	Source of food, medicine and material. Used repelling in snakes	
Ficus capensis	Mukuyu	23.8	18.9	Broad	Bough bark, editable fruits, medicinal, shade tree	
Combretum zeyheri	Mukenge	22.4	17.5	Broad	Source of food, medicine and material for making baskets	
Syzygium guineense	Umufinsa	12.8	14.6	Broad	Medicinal, food and source of wood	
Rauvolfia caffra	Umubimbi	10.4	13.5	Broad	Medicinal, source of wood and food. Agroforestry purposes	
Combretum zeyheri	Mukenge	21.34	15.5	Broad	Source of food, medicine and material for making baskets	
Acacia polyacantha	Munganushi	19.22	22.2	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	22.92	18.68	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	19.72	15.37	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	33.4	20.7	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	32.2	23.5	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Syzygium guineense	Chibumbya	15.8	10.4	Broad	Medicinal, food and source of wood	
Acacia polyacantha	Munganushi	15.92	7.3	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	16.8	9.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	15.92	7.4	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Combretum zeyheri	Mukenge	18.49	17.5	Broad	Source of food, medicine and material for making baskets	
Acacia polyacantha	Munganushi	17.2	11	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Terminalia mollis	Ichibobo	23.76	24.4	Broad	Bark on trunk deeply fissured	

Appendix 6 cont…

Plot 5 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Combretum zeyheri	Mukenge	22.69	22.4	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	25.99	21.75	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	18.2	19.5	Broad	Source of food, medicine and material for making baskets	
Acacia polyacantha	Munganushi	23.42	18.5	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	11.92	13.5	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Syzygium guineense	Umufinsa	20.4	14.6	Broad	Medicinal, food and source of wood	
Ficus capensis	Mukuyu	32.68	22.9	Broad	Rough bark, editable fruits, medicinal, shade tree	
Terminalia mollis	Ichibobo	20.56	19.9	Broad	Bark on trunk deeply fissured	
Acacia polyacantha	Munganushi	20.92	16.87	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Ficus capensis	Mukuyu	24.04	20.9	Broad	Rough bark, editable fruits, medicinal, shade tree	
Ficus capensis	Mukuyu	26.8	21.9	Broad	Rough bark, editable fruits, medicinal, shade tree	
Syzygium guineense	Chibumbya	5.8	4.5	Broad	Medicinal, food and source of wood	Clay, Silt
Combretum zeyheri	Mukenge	18.49	17.5	Broad	Source of food, medicine and material for making baskets	
Syzygium guineense	Chibumbya	26.78	13.56	Broad	Medicinal, food and source of wood	
Acacia polyacantha	Munganushi	16.68	24.68	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Ficus capensis	Mukuyu	29.8	24.9	Broad	Rough bark, editable fruits, medicinal, shade tree	
Acacia polyacantha	Munganushi	10.55	14.5	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	24.42	23.5	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	25.4	23.25	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Acacia polyacantha	Munganushi	13.12	16.4	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Combretum zeyheri	Mukenge	19.19	14.35	Broad	Source of food, medicine and material for making baskets	
Combretum zeyheri	Mukenge	16.9	12.5	Broad	Source of food, medicine and material for making baskets	
Acacia polyacantha	Munganushi	25.42	23.67	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	

Appendix 7: Forest inventory data collected (Dry season: 22nd to 30th September, 2022, Wet season: 6th to 14th April, 2023 and 03rd to 23rd May2023) in Kalahari Woodland, Ngabwe, Zambia.

Kalahari Woodland						
Plot 1 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Xylopia odoratissima	Mukondekonde	12.41	12.59	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	Sandy
Xylopia odoratissima	Mukondekonde	5.9	2.3	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Xylopia odoratissima	Mukondekonde	5.73	8	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Xylopia odoratissima	Mukondekonde	28.65	18	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Xylopia odoratissima	Mukondekonde	18.86	3	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Brachystegia boehmii	Musamba	32.78	22	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	47.42	21	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	34.06	22	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	12.73	21	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	75.44	23	Broad	Source of fibre and timber	
Diplorhynchus condylocarpon	Mwenge	18.46	14	Broad	Rough bark, timber, latex, fibre and medicinal virtues	
Xylopia odoratissima	Mukondekonde	9	10.78	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Anisophyllea boehmii	Mufungo	5.73	8	Broad	Edible fruit and useful wood	
Pericopsis angolensis	Mubanga	28.01	17.6	Broad	Collected for poles, firewood and medicinal purposes	
Pericopsis angolensis	Mubanga	19.1	15	Broad	Collected for poles, firewood and medicinal purposes	
Swartzia madagascariensis	Ndale	13.21	10	Broad	Bark dark grey rough and fissured, multi-purpose wood use	
Afzelia quanzensis	Mupapa	12.41	11	Broad	Medicinal, food and source of wood	
Afzelia quanzensis	Mupapa	5.5	4	Broad	Medicinal, food and source of wood	
Swartzia madagascariensis	Ndale	8.91	12	Broad	Bark dark grey rough and fissured, multi-purpose wood use	
Pterocarpus angolensis	Mukwa	7.96	11	Broad	Used Timber, medicinal and agroforestry purposes	
Parinari curatellifolia	Mupundu	5.86	1.5	Broad	Bears editable fruits: Medicinal: agroforestry	
Parinari curatellifolia	Mupundu	51.57	22.6	Broad	Bears editable fruits: Medicinal: agroforestry	
Pterocarpus angolensis	Mukwa	36.92	19	Broad	Used Timber, medicinal and agroforestry purposes	
Parinari curatellifolia	Mupundu	5.86	14	Broad	Bears editable fruits: Medicinal: agroforestry	

Appendix 7 cont…

Plot 2 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Senegalia polyacantha	Munga	60.16	29.5	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	Sandy
Senegalia polyacantha	Munga	42.02	26.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Senegalia polyacantha	Munga	15.28	13.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Senegalia polyacantha	Munga	16.55	15.5	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Senegalia polyacantha	Munga	34.06	17.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Senegalia polyacantha	Munga	28.33	18.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Senegalia polyacantha	Munga	36.6	18.6	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Senegalia polyacantha	Munga	44.56	21	Broad	Medicinal, source of wood and food. Used repelling in snakes/crocodile	
Parinari curatellifolia	Mupundu	55.57	25.6	Broad	Bears editable fruits: Medicinal: agroforestry	
Albizia antunesiana	Musase	12.73	10	Broad	Local use as a source of medicines, food, wood and tannins	
Julbernardia globiflora	Mpanse	27.41	19.35	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Phyllocosmus lemaireanus	Umusengameno	5.18	2.55	Broad	Bark rough with brick-red slash	
Julbernardia globiflora	Mpanse	28.01	21.5	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Anisophyllea pomifera	Mfungo	5.82	2	Broad	Edible fruit and useful wood	
Julbernardia globiflora	Mpanse	28.01	21.5	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Brachystegia boehmii	Musamba	35.42	21.43	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	41.42	20.9	Broad	Source of fibre and timber	
Julbernardia globiflora	Mpanse	26.23	21.34	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	29.40	22.95	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Pericopsis angolensis	Mubanga	19.1	15	Broad	Collected for poles, firewood and medicinal purposes	
Swartzia madagascariensis	Ndale	13.21	10.4	Broad	Bark dark grey rough and fissured, multi-purpose wood use	
Xylopia odoratissima	Mukondekonde	23.86	15.47	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Xylopia odoratissima	Mukondekonde	20.86	18.3	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Xylopia odoratissima	Mukondekonde	27.86	17.4	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Brachystegia boehmii	Musamba	39.42	21.32	Broad	Source of fibre and timber	
Xylopia odoratissima	Mukondekonde	13.56	7.4	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	

Appendix 7 cont…

Plot 3 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Oldfieldia dactylophylla	Mulwalwa	6.37	4	Broad	Medicinal, source of wood and food	Sandy
Julbernardia globiflora	Mpanse	10.82	14.6	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Brachystegia boehmii	Musamba	26.41	19	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	26.1	19	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	22.92	19	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	14.64	16	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	14	16.5	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	32.79	22.5	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	20.37	18	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	27.7	21	Broad	Source of fibre and timber	
Julbernardia globiflora	Mpanse	28.01	21.5	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	34.06	22.59	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	25.46	22.6	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	10.19	17	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	34.06	22.59	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Hexalobus monopetalus	Funtwa	5.8	2.5	Broad	Medicinal, source of fibre and food	
Hexalobus monopetalus	Funtwa	5.8	2.5	Broad	Medicinal, source of fibre and food	
Monotes africana	Muchenje	5.4	1.6	Broad	Local use of its wood in construction	
Monotes africana	Muchenje	5.41	2.5	Broad	Local use of its wood in construction	
Monotes katangensis	Chimpapa	33.1	21.6	Broad	Medicinal, used to heal wounds	
Monotes katangensis	Chimpapa	24.8	18.6	Broad	Medicinal, used to heal wounds	
Monotes katangensis	Chimpapa	21.64	18.6	Broad	Medicinal, used to heal wounds	
Julbernardia globiflora	Mpanse	13.36	13	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	20.7	19	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	27	22	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	24.83	20.6	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	23.87	20.86	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	16.87	18	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	

Appendix 7 cont…

Plot 4 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Xylopia odoratissima	Mukondekonde	8.6	3.5	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	Sandy
Xylopia odoratissima	Mukondekonde	7.9	3.5	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Xylopia odoratissima	Mukondekonde	8.9	3.5	Broad	Bark pale to dark grey, roughly fissured. Drink stimulating	
Brachystegia boehmii	Musamba	19.08	12	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	32.78	17.6	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	14.32	11	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	30.55	16	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	23.87	14	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	21.64	24	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	14.32	11	Broad	Source of fibre and timber	
Brachystegia boehmii	Musamba	32.78	17.6	Broad	Source of fibre and timber	
Combretum zeyheri	Mufuka	19.73	12	Broad	Source of food, medicine and material for making baskets	
Albizia antunesiana	Mukoso	20.69	21.5	Broad	Local use as a source of medicines, food, wood and tannins	
Albizia antunesiana	Mukoso	19.1	20.5	Broad	Local use as a source of medicines, food, wood and tannins	
Albizia antunesiana	Mukoso	13.69	13	Broad	Local use as a source of medicines, food, wood and tannins	
Albizia antunesiana	Mukoso	16.55	18	Broad	Local use as a source of medicines, food, wood and tannins	
Diospyros batocana	Muntu	5.3	5.3	Broad	Bark dark, rough and deeply fissured. Edible fruits	
Oldfieldia dactylophylla	Mulwalwa	6.86	2.3	Broad	Medicinal, source of wood and food	
Julbernardia globiflora	Mpanse	35.01	21	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	33.1	20	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	41.38	22	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	37.24	21	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	25.15	19	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	25.15	19	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	24.5	18	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	18.46	15	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	26.74	18	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	26.1	18	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	

Appendix 7 cont…

Plot 5 (30m x 30m sample plot)						
Species Scientific Name	**Local Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Julbernardia globiflora	Mpanse	50.93	22.6	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	40.74	22.5	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	34.38	19	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	mpanse	39.47	22	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	39.79	23.6	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	27.69	19	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	mpanse	44.88	22.6	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	35.65	22	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	19.1	17	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	20.69	17	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	25.46	17	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	22.6	17	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Julbernardia globiflora	Mpanse	25.76	18.5	Broad	Bark on trunk rough, source of fibre, wood and medicinal purpose	
Afzelia quanzensis	Mupapa	34.7	22	Broad	Medicinal, food and source of wood	Sandy
Afzelia quanzensis	Mupapa	16.55	20	Broad	Medicinal, food and source of wood	
Afzelia quanzensis	Mupapa	5.41	10	Broad	Medicinal, food and source of wood	
Afzelia quanzensis	Mupapa	9.23	12	Broad	Medicinal, food and source of wood	
Afzelia quanzensis	Mupapa	11.78	10	Broad	Medicinal, food and source of wood	
Afzelia quanzensis	Mupapa	6.68	3	Broad	Medicinal, food and source of wood	
Afzelia quanzensis	mupapa	9.55	15.6	Broad	Medicinal, food and source of wood	
Amblygonocarpus andongensis	Musengamena	5.18	2	Broad	Medicinal, source of food, wood and fuel	
Amblygonocarpus andongensis	Musengamena	5.5	1.6	Broad	Medicinal, source of food, wood and fuel	
Amblygonocarpus andongensis	Musengamena	7.32	5	Broad	Medicinal, source of food, wood and fuel	
Amblygonocarpus andongensis	Musengamena	5.18	2	Broad	Medicinal, source of food, wood and fuel	

Appendix 8: Forest inventory data collected (Wet season: 6th to 14th April, 2023 and 03rd to 23rd May2023) in Mufulira, Zambia.

Eucalyptus Plantation						
Plot 1 (30m x 30m sample plot)						
Species Scientific Name	**Common Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Eucalyptus grandis	gum tree	23.74	41.37	Narrow	Smooth bark. Used in supporting structure, sawn timber	Sandy loam
Eucalyptus grandis	gum tree	27.95	40.59	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	25.95	40.15	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	24.38	41.36	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	25.94	43.83	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	22.39	40.87	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	20.57	46.89	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	25.37	45.38	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	28.94	42.76	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	28.59	43.18	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	22.87	42.67	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	24.37	43.26	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Plot 2 (30m x 30m sample plot)						
Eucalyptus grandis	gum tree	25.34	42.36	Narrow	Smooth bark. Used in supporting structure, sawn timber	Sandy loam
Eucalyptus grandis	gum tree	26.35	41.57	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	23.45	43.45	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	21.38	42.62	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.34	43.63	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.49	42.36	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	27.47	43.49	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.57	42.78	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.08	39.42	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.39	44.6	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	27.47	40.37	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	25.36	44.46	Narrow	Smooth bark. Used in supporting structure, sawn timber	

Appendix 8 cont…

Plot 3 (30m x 30m sample plot)						
Species Scientific Name	**Common Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Eucalyptus grandis	gum tree	24.34	43.36	Narrow	Smooth bark. Used in supporting structure, sawn timber	Sandy loam
Eucalyptus grandis	gum tree	25.35	43.57	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	27.45	42.45	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.38	41.6	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	27.44	41.83	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	25.69	40.87	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	24.57	44.79	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	22.37	41.38	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	28.34	39.76	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	28.59	43.8	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.87	41.47	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	25.37	40.26	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	20.57	43.73	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Plot 4 (30m x 30m sample plot)						
Eucalyptus grandis	gum tree	27.47	40.25	Narrow	Smooth bark. Used in supporting structure, sawn timber	Sandy loam
Eucalyptus grandis	gum tree	28.74	42.3	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	23.46	38.67	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	27.45	39.28	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.34	38.37	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	25.63	43.73	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.43	39.78	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	29.38	40.23	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	28.54	39.36	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	27.46	44.63	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.73	40	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	20.74	35.68	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	18.76	34.68	Narrow	Smooth bark. Used in supporting structure, sawn timber	

Appendix 8 cont…

Plot 5 (30m x 30m sample plot)						
Species Scientific Name	**Common Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Eucalyptus grandis	gum tree	20.9	28.68	Narrow	Smooth bark. Used in supporting structure, sawn timber	Sandy loam
Eucalyptus grandis	gum tree	20.14	31.34	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	20.47	29.39	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	23.64	32.44	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	22.45	31.4	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	24.7	30.98	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	20.34	30	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	26.2	29	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	23.79	31	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	18.5	27.9	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	21.04	28.5	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	25.4	30.4	Narrow	Smooth bark. Used in supporting structure, sawn timber	
Eucalyptus grandis	gum tree	20.7	29	Narrow	Smooth bark. Used in supporting structure, sawn timber	

Appendix 8 cont…

Pine Plantation						
Plot 1 (30m x 30m sample plot)						
Species Scientific Name	**Common Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Pinus Kesiya	Khasi pine	22.31	40.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	Sandy loam
Pinus Kesiya	Khasi pine	20.7	44.13	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.87	42.2	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	23.65	41.18	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	23.86	43.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.78	42.22	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	23.42	41.71	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	23.64	42.32	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.53	41.51	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	24.44	44.23	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.78	42.5	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	24.46	42.14	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Plot 2 (30m x 30m sample plot)						
Pinus oocarpa	Khasi pine	24.1	42.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	Sandy loam
Pinus oocarpa	Khasi pine	23.17	41.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	24.87	43.12	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	23.55	42.18	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	22.86	45.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	22.78	43.22	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	22.42	43.21	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	24.06	41.42	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	22.43	41.31	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	22.44	45.23	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	24.78	43.5	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	25.44	42.44	Narrow	Dark brown rough bark. Used for sawn lumber or planks	

Appendix 8 cont…

Pine Plantation						
Plot 3 (30m x 30m sample plot)						
Species Scientific Name	**Common Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Pinus Kesiya	Khasi pine	22.41	44.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	Sandy loam
Pinus Kesiya	Khasi pine	22.7	44.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.87	43.2	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	23.65	43.18	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.86	44.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	24.78	43.22	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	21.42	42.21	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	24.06	41.22	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	23.73	43.21	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	24.44	44.23	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.78	43.5	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	24.46	42.14	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	23.2	41.5	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Plot 4 (30m x 30m sample plot)						
Pinus oocarpa	Khasi pine	25.73	42.8	Narrow	Dark brown rough bark. Used for sawn lumber or planks	Sandy loam
Pinus oocarpa	Khasi pine	22.01	37.6	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	25.1	39.15	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	23.21	40.10	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	21.41	35.91	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	25.67	42.54	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	27.91	39.12	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	26.96	37.58	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	25.86	41.5	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	21.57	42.6	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	26.92	39.93	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	22.86	39.43	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus oocarpa	Khasi pine	26.46	37.4	Narrow	Dark brown rough bark. Used for sawn lumber or planks	

Appendix 8 cont…

Pine Plantation						
Plot 5 (30m x 30m sample plot)						
Species Scientific Name	**Common Name**	**DBH (cm)**	**H (m)**	**Leaves**	**Special features/Characteristics/Uses**	**Soil Profile at 10cm**
Pinus Kesiya	Khasi pine	24.41	30.59	Narrow	Dark brown rough bark. Used for sawn lumber or planks	Sandy loam
Pinus Kesiya	Khasi pine	30.9	42.3	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	25.43	42.46	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	24.65	41.34	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	25.86	43.83	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.78	42.13	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	27.42	41.34	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	24.06	42	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	25.73	41.5	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	25.44	43.2	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	22.15	42.5	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	28.46	36	Narrow	Dark brown rough bark. Used for sawn lumber or planks	
Pinus Kesiya	Khasi pine	25.2	41.5	Narrow	Dark brown rough bark. Used for sawn lumber or planks	

Appendix 9: Ethical Clearance Letter for the study in the UKRSB, Zambia.

THE UNIVERSITY OF ZAMBIA
DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road Campus | P.O. Box 32379 | Lusaka10101 | Tel: +260-211-290 258/291 777 **Fax**: (+260)-211-290 258/253 952 | E**-mail**: director.drgs@unza.zm | Website: www.unza.zm

APPROVAL OF STUDY

IORG No. 0005376
NASREC IRB No. 00006465

19th September, 2022

REF NO. NASREC-2019-JUL-017

Muyaka Kamamba
The University of Zambia
School of Mines
P.O. Box 32379
LUSAKA

Dear Mr. Muyaka Kamamba,

RE: "EXPLORING FOREST-WATER NEXUS IN A CHANGING ENVIRONMENT OF KAFUE RIVER BASIN, ZAMBIA"

Reference is made to your submission of the protocol captioned above. The NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	**ORDINARY REVIEW**	**APPROVAL NO. NASREC-2022-JUL-017**
Approval and Expiry Date	Approval Date: 19th September, 2023	Expiry Date: 18th September, 2023
Protocol Version and Date	Version - Nil.	18th September, 2023
Information Sheet, Consent Forms and Dates	English.	To be provided
Consent form ID and Date	Version - Nil	To be provided
Recruitment Materials	Nil	Nil
Other Study Documents	Questionnaire.	
Number of Participants Approved for Study		

Appendix 9 cont…

Specific conditions will apply to this approval. As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

CONDITIONS OF APPROVAL

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.
- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 5 days.
- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.
- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.
- Principal investigators are responsible for initiating Continuing Review proceedings. HSSREC will only approve a study for a period of 12 months.
- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.
- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled "late submissions" and will incur a penaltyfee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.
- Every 6 (six) months a progress report form supplied by The University of Zambia Natural and Applied Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.
- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO), both NASREC and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.
- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.
- Filing a closing report (rather than just letting your approval lapse) is important as it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.

Appendix 9 cont…

- A reprint of this letter shall be done at a fee.

- All protocol modifications must be approved by NASREC by way of an application for an amendment prior to implementation unless they are intended to reduce risk (butmust still be reported for approval). Modifications will include any change of investigator/s or site address or methodology and methods. Many modifications entailminimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alterthe risk-benefit ratio, may require Full Board review. In all cases, except where notedabove regarding subject safety, any changes to any protocol document or proceduremust first be approved by NASREC before they can be implemented.

Should you have any questions regarding anything indicated in this letter, please do not hesitate to getin touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry out your study.Yours

faithfully,

Dr.E. M. Mwanaumo

DR. E. M. MWANAUMO

CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCES RESEARCHETHICS COMMITTEE - IRB

cc: Director, Directorate of Research and Graduate Studies
Assistant Director (Research), Directorate of Research and Graduate Studies Assistant Registrar (Research), Directorate of Research and Graduate Studies

Appendix 10: Monthly Average AET rates (mm month^{-1}) for the UKRSB, Zambia from 2013 to 2022.

	2022	2021	2020	2019	2018	2017	2016	2015	2014	2013
31-Oct	88.79	106.12	107.26	117.71	119.45	105.53	106.52	125.84	111.55	122.48
30-Nov	95.44	105.05	95.88	97.33	111.68	102.40	106.83	104.08	120.20	141.69
31-Dec	105.91	114.78	92.31	85.82	101.37	110.04	111.31	110.16	91.91	120.06
31-Jan	90.79	91.50	108.56	108.32	130.27	103.62	116.96	85.00	109.09	110.82
28-Feb	81.27	90.26	101.83	115.86	101.94	97.39	109.39	85.06	89.82	103.07
31-Mar	101.28	102.07	109.72	140.26	110.81	99.74	115.39	104.87	112.66	114.33
30-Apr	91.61	93.81	107.43	118.43	92.71	93.98	87.95	80.08	99.21	113.04
31-May	93.38	77.73	87.05	109.71	78.22	86.57	69.23	75.00	93.57	90.20
30-Jun	59.32	57.46	64.28	79.59	62.79	72.70	56.06	58.29	76.99	74.26
31-Jul	56.16	51.94	53.46	77.98	56.04	70.63	57.94	61.21	70.82	66.93
31-Aug	65.49	60.96	70.52	70.49	67.33	71.68	67.84	59.24	66.98	73.31
30-Sep	55.22	66.38	76.64	74.69	80.17	68.62	94.81	72.48	66.28	91.38