LAND USE AND LAND COVER RE-PATTERNING AS A METHOD FOR STREAMFLOW REGIME MODIFICATION IN LILONGWE RIVER CATCHMENT IN MALAWI

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A THESIS SUBMITTED TO THE FACULTY OF ENVIRONMENTAL SCIENCES, DEPARTMENT OF WATER AND SANITATION IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN WATER RESOURCES MANAGEMENT AND DEVELOPMENT

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DECLARATION

I hereby declare that this thesis titled, "*Land Use and Land Cover Re-patterning as a Method for Streamflow Regime Modification in Lilongwe River Catchment in Malawi"* has been written by me and is a record of my research work. All citations, references, and ideas borrowed from other sources have been duly acknowledged. This thesis is being submitted in partial fulfilment of the requirements for the award of a Master of Science Degree in Water Resources at Mzuzu University. None of the present work has been submitted previously for any degree or examination at any other University.

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CERTIFICATE OF COMPLETION

The undersigned certify that this thesis is a result of the author's work and that to the best of our knowledge, it has not been submitted for any other academic qualification within Mzuzu University or elsewhere. The thesis is acceptable in form and content, and that satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate through an oral examination held on 11th November, 2021.

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ABSTRACT

Land use and land cover changes (LULCCs) have been increasingly shown to exacerbate water-related problems such as floods and droughts worldwide. Malawi has not been spared such issues despite the reported opportunities for ameliorating the same through land use or cover (LUC) re-patterning. Using Lilongwe River Catchment as a case in point, this study set out to assess LUC re-patterning as a method for modifying streamflow regimes in Malawi. The study assessed the period from 2020 to 2049 and it was conducted by initially identifying the current land cover pattern in Lilongwe River Catchment using remote sensing techniques such as atmospheric correction and image classification. The streamflow regime resulting from this land cover pattern was then determined using a hydrological model known as the Soil Water Assessment Tool (SWAT), and climate modelling techniques. Practical land use patterns for the catchment were then determined using the Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) model. An ideal streamflow regime was then later defined based on information obtained from a systematic review of literature, existing legal instruments and institutional frameworks governing land use planning in Malawi. The effect of each land use scenario (n = 6) on the Lilongwe River flow regime was then examined to determine which scenario yielded ideal streamflow requirements for the catchment under different climatic conditions (n = 3). Calibration and validation of the SWAT model yielded satisfactory values of Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2) of 0.65 and 0.64 for the calibration period, and 0.62 and 0.62 for the validation period respectively. Results of the study demonstrated that all identified land use scenarios improved the river's streamflow regime, though not enough to meet the minimum 2049 projected demand of 5 m^3/s. The best combination of land use and climate scenario yielded potentially helpful positive changes of up to

+4% (0.5 m^3/s) in dry season flow and +3% (0.8 m^3/s) in wet season flow. It was thus concluded that LUC re-patterning may not be the best tool for modifying streamflow regimes in Lilongwe river catchment. Some evidence suggests repetition of this study in other catchments in Malawi may however show variations against the current conclusion since hydro-climatic conditions vary across the country. Further assessments on the same are thus strongly recommended.

DEDICATION

This work is dedicated to my father and mother, Mr. and Mrs. Hyde and Stella Sibande, as well as my dear sister Louisa, cousins, and friends whose financial and moral support has pushed me to achieve all I have today. I am truly grateful. I also thank the rest of my family for always being there for me.

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ACRONYMS AND ABBREVIATIONS

DEM	Digital Elevation Model
EROS	Earth Resources Observation and Science
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographical Information Systems
GPS	Global Positioning System
GoM	Government of Malawi
HEC-HMS	Hydrologic Engineering Centre Hydrologic Modelling System
HEC-RAS	Hydrologic Engineering Center's River Analysis System
IPCC	Intergovernmental Panel on Climate Change
LULCC	Land Use and Land Cover Change
LWB	Lilongwe Water Board
MAIWD	Ministry of Agriculture, Irrigation, and Water Development
MDCCMS	Malawi Department of Climate Change and Meteorological Services
MSF	Medicins Sans Frontieres
NPDP	National Physical Development Plan
NRGI	Natural Resources Governance Institute
NSO	National Statistical Office
NWRA	National Water Resources Authority
OLI	Operational Land Imager
SWAT	Soil Water Assessment Tool
SWAT-CUP	Soil Water Assessment Tool - Calibration and Uncertainty Programs
UN-DESA	United Nations Department of Economic and Social Affairs
UNICEF	United Nations Children’s Fund
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey

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CHAPTER ONE: INTRODUCTION

1.1 Background

The world human population is rapidly growing at an annual rate of 1.09 % (Cleland 2013; United Nations Department of Economic and Social Affairs (UN-DESA) 2017). A general concern has thus emerged in the scientific community that this rapid growth is compromising the sustainability of natural resources (Grebner, Bettinger & Siry 2012; UN-DESA 2013; Goldin 2014; Baus 2017). For example, largely as a result of population increase, among other factors, the Amazon Rainforest in South America has reportedly lost 13.3 % of its forest cover through deforestation between 1970 and 2013, amounting to 811,662 km^2 (*Rede Amazônica de Informação Socioambiental Georreferenciada* 2015).

Despite possessing an abundance of resources (Kurečić 2016; Natural Resources Governance Institute (NRGI) 2017), Africa's rapid population growth and poor management practices are taking their toll on the continent's natural resources (Witte *et al.* 2013; NRGI 2017). Malawi has not been spared from this challenge. Possessing one of the highest annual population growth rates in the world, at 2.9 %, and an estimated population of 17.6 million in 2018 (National Statistical Office 2018), its natural resources are facing increasing anthropogenic pressure (Government of Malawi 2010; GoM 2012b; Katumbi, Nyengere & Mkandawire 2015). With special reference to Integrated Water Resources Management (IWRM), one essential resource, particularly under threat in Malawi, is land.

The term "land" used in this context does not simply refer to soil and surface topography, but also the features such as water, deposits, plants, and animals existing on and within it (Di Gregorio & Jansen 2005; Fisher *et al*. 2005). Malawi has an estimated land area of 94,080 km^2 (GoM 1996), and about 80 % of its population relies on produce from smallholder farming (United States Agency for International Development 2017). Coupled with pressure from the growing economy, land resources in the country are being strained (GoM 2002; GoM 2010; Kirui 2016). It therefore comes as no surprise that one area that has faced a lot of changes in land use and land cover in Malawi is the Lilongwe River Catchment in Lilongwe district (Munthali 2013; Manda 2015). The catchment comprises the Dzalanyama Forest Reserve, which is located south west of Lilongwe and has experienced many challenges with regard to encroachment, deforestation, and other human activities (Munthali & Murayama 2011; Kamchacha 2016). These changes have great significance in part because of their bearing towards another precious resource under threat in Lilongwe which is, water (GoM 2012a; Mpakati-Gama & Mkandawire 2015; World Bank 2017; Tajbakhsh, Memarian & Kheyrkhah 2018).

Lilongwe City has many competing uses of water, the majority of which is sourced from the Lilongwe River (Katumbi *et. al* 2015; World Bank 2017). However, as a result of population growth, economic growth, and climate change factors, water demand from the river is rapidly increasing and the Lilongwe River Catchment is facing a water crisis (GoM 2012a; World Bank 2017; Makwiza *et al.* 2018). Recent studies suggest that changes in land use and land cover (LULCC) may have been a factor in exacerbating these problems (Welde & Gebremariam 2017; Kundu, Khare & Mondal 2017; Sibande *et al.* 2020).

Several studies in the field of hydrology such as by Mbano *et al.* (2009), Geremew (2013), Yao *et al*. (2012), and Palamuleni, Marco Ndomba & Annegarn (2011) have shown that LULCC have the potential to influence the hydrologic regime of a river by reducing or increasing runoff and infiltration in the catchment. This phenomenon has also been observed in the Lilongwe River Catchment according to a study by Sibande *et al*. (2020). The study revealed that in the years between 1989 and 2004, LULCC in the

Lilongwe River Catchment caused an increase in the average streamflow in the river of about 1.432m^3/s (123,724 m^3/day) during the wet season, and a decrease of about 0.058m^3/s (5,011 m^3/day) during the dry season. This was attributed to the decrease in forest cover (10.7 %) and the increase of cropland (8.6 %) and settlements (3.5 %) in the catchment which altered its hydrological processes. The ramifications of more LULCC on streamflow may be more magnified over a longer period (Lei & Zhu 2018; Geremew 2013; Hassaballah *et al.* 2017).

These changes in streamflow may have exacerbated the recent floods and water scarcity problems affecting the city during the wet (Medicins Sans Frontieres Geographical Information System (MSF-GIS) Unit 2017; United Nations Children's Fund 2017) and dry season respectively (Mpakati-Gama & Mkandawire 2015; World Bank 2017). However, it stands to reason that reversing this phenomenon is equally possible if current land use patterns in the Lilongwe River Catchment were restructured or re-patterned. This therefore may present an opportunity for land use planners to strategically influence streamflow within the river and better cater for the needs of river's beneficiaries if proper land use plans are developed and executed.

1.2 Problem Statement

Lilongwe River is the main source of municipal water for the residents of Lilongwe City (World Bank 2017). According to the Lilongwe Water Board 2004 Annual Report (Lilongwe Water Board 2005), the utility experienced a peak water demand of 0.971 m^3/s (83,919.5 m^3/day) during the dry season. Assuming all water in the river was used by the utility, the findings of Sibande *et al*. (2020) imply that the amount of water rendered inaccessible due to LULCC in 16 years could have supplied Lilongwe City with water for a complete 7 days during that same season. This assumption merely showcases the severity of the situation, but in reality, the reduction in streamflow may have also negatively affected the many other users of the river, including irrigation schemes, plants, and wildlife.

Despite the above mentioned, current land use planning practices in Malawi do not take into consideration the potential effect that proposed land uses have on the quantity of water in streams. The National Physical Planning and Development Management Guidebook (GoM 2011) for example, acknowledges the importance of preserving river catchments among other things, but only frames provisions therein in the interest of preserving water quality, and never quantity. All changes in land use within the Lilongwe River Catchment, whether purely accidental or intentional, may therefore lead to unpredictable changes in the streamflow of Lilongwe River and consequently affect its water supplying capability depending on the type and magnitude of LULCC taking place.

Population in Lilongwe is increasing at an intercensal rate of 3.8 % (NSO 2018) and, as a result, land use changes are bound to occur as the demand for land resources increases as well. Thus, an opportunity may exist to influence streamflow in favour of the beneficiaries of the river by developing and executing proper land use planning. Considering the bulk water deficit of 94,000 m^3 per day in municipal supply predicted to face Lilongwe City by 2025 (GoM 2012a; World Bank 2017), failure to exploit this opportunity may therefore forgo a cost-effective source of water. This is particularly important in the area considering the alternatives being considered such as the Salima-Lilongwe Water Supply, and Diamphwe Dam projects are very costly.

1.3 Study Objective

To explore land use and land cover re-patterning as a method for modifying streamflow regime in the Lilongwe River Catchment.

1.4 Specific Objectives

A. To project the streamflow regime of the Lilongwe River from 2020 to 2049 based on the current land use pattern.

B. To determine practical land use patterns for Lilongwe River Catchment based on ideal streamflow requirements of the river.

C. To determine the effect of different land use patterns on the streamflow regime of Lilongwe River from 2020 to 2049.

1.5 Research Questions

A. What is the predicted streamflow regime of the Lilongwe River from 2020 to 2049 based on the current land use pattern?

B. What legally feasible and practical land use patterns can be used to positively influence Lilongwe River's streamflow regime?

C. What is the effect of different land use patterns on the streamflow regime of Lilongwe River?

1.6 Significance of the Study

The results of the study could help land use planners take into consideration the effects of both old and new developments on streamflow when allocating land. In conjunction with water managers, this would facilitate informed decision-making on appropriate mitigation or enhancement measures where relevant.

Furthermore, considering the inevitability of land use changes in all parts of the world, the study findings may apply to many other catchments and inform decision-making on water related issues, or help alleviate some water related problems such as floods. This not only contributes to the body of knowledge on the topic, but upon further research may facilitate the development of an all-in-one digital model that may be calibrated and used for specific catchments across the country. This is an exciting prospect especially since well-proven land use and hydrological models applicable to Malawi already exist. Such a development would allow quick simulation of the hydrological effects of new projects at their conception stage, and thus facilitate informed project design.

CHAPTER TWO: LITERATURE REVIEW

2.1 Theoretical Framework

The nature of the factors influencing the distribution and movement of water resources on earth is a subject that has been pondered since ancient times. Texts as old as the Old Testament of the Christian Bible notably contain passages that describe hydrologic processes. The Books of Amos, and Ecclesiastes for example, which date back to the eighth (Maier 2004) and tenth (Metzger & Coogan 2004) centuries BC respectively, briefly describe the concepts of evaporation, precipitation, and runoff by highlighting that water that flows from rivers into the sea and eventually returns to the land as rain (see Amos 5:8, and Ecclesiastes 1:7).

Other ancient scholars from across Europe and Asia hypothesised individual mechanisms of hydrological processes. Greek philosophers such as Aristotle (*c.* 350 BC) for instance, hypothesized the upwelling of underground water to springs through what is now known as capillary rise (Rodda *et al.* 2004; Brutsaert 2005). Another Greek scholar, Anaximander (*c.* 610 BC), is credited as being the first to postulate that rather than sea water infiltrating through the soil to create rivers (a popular notion at the time), rivers are fed by rainfall which percolates into, and seeps from the ground respectively (Brutsaert 2005). Xenophanes (*c.* 530 BC) (Lesher 1978; Koutsoyiannis, Mamassis & Tegos 2007) a Greek scholar, and Chinese scholars Chi Ni Tzu (*c.* 320 BC) and Lu Shih Ch'un Ch'iu (*c.* 239 BC) (Rodda *et al.* 2004) among other things theorized the significant contribution of groundwater to streamflow.

The Greek scholar Anaxagoras (*c.* 460 BC) was the first known to postulate that various hydrological processes function in a closed cycle involving the movement and storage of water (Rodda *et al.* 2004; Brutsaert 2005; Koutsoyiannis *et al.* 2007). However, a common error in his and most other scholars' understanding at the time was the staunch belief that rainfall was insufficient to account for all the water in springs and rivers (Rodda *et al.* 2004; Brutsaert 2005).

It was not until 1580 that Bernard Palissy, a French potter and writer, became the first published scholar to assert that rainfall alone was sufficient for the maintenance of rivers (Deming 2005; Brutsaert 2005; Karterakis *et al.* 2007). Palissy hypothesized that rainfall formed part of an ongoing cycle of hydrological processes and upon scientific testing by Pierre Perrault in 1674, marked the discovery of the full set of hydrological processes which form what is widely known as the modern theory of the hydrological cycle (Deming 2005; Deming 2014; Brutsaert 2005; Karterakis *et al.* 2007).

2.1.1 The Hydrological Cycle

The hydrologic cycle, also known as the water cycle, may be defined as a continuous series of hydrological processes that describe the storage and movement of water between the earth's atmosphere, lithosphere, and biosphere (Munn 2002; Brutsaert 2005; Gregory *et al.* 2009; Bethea 2011). Figure 2.1 illustrates the network of hydrological processes involved in the hydrological cycle.

By its nature, the hydrologic cycle has neither a beginning nor an end. However, considering that the bulk of the earth's water is stored in oceans, it is logical to consider the cycle as beginning with the direct effect of its main driving force, the sun's radiation, on the oceans (Gregory *et al.* 2009; Bethea 2011). This radiation causes heating of the ocean's surface which in turn causes evaporation, the conversion of liquid water to water vapour to form part of the atmosphere (Brutsaert 2005; Gregory *et al.* 2009; Bethea 2011). Through a combination of favourable meteorological conditions, the water vapour changes back to its liquid state through a process known as condensation and with favourable atmospheric conditions precipitates back to the earth's surface as rain, dew, snow, and so on (Brutsaert 2005; Gregory *et al.* 2009; Bethea 2011).

Precipitation may collect on vegetation or other land surfaces and is stored as interception before evaporating back to the atmosphere shortly after (Brutsaert 2005; Gerrits 2010) Alternatively, precipitation that reaches the ground may infiltrate into a land surface through gaps in the soil or fractures in rocks (Brutsaert 2005; Bethea 2011). This water may then flow within the soil as subsurface flow, which is mainly responsible for sustaining streams during dry conditions, or may percolate deep into the water table (Brutsaert 2005; Karterakis *et al.* 2007; Wangpimool *et al.* 2013). Precipitated water may also flow over the surface in the form of overland flow or surface runoff which tends to collect locally, either in small depressions such as ponds or puddles or in larger channels where it continues as streamflow. This streamflow ultimately discharges water into oceans from which it will eventually evaporate again, thus completing the water cycle.

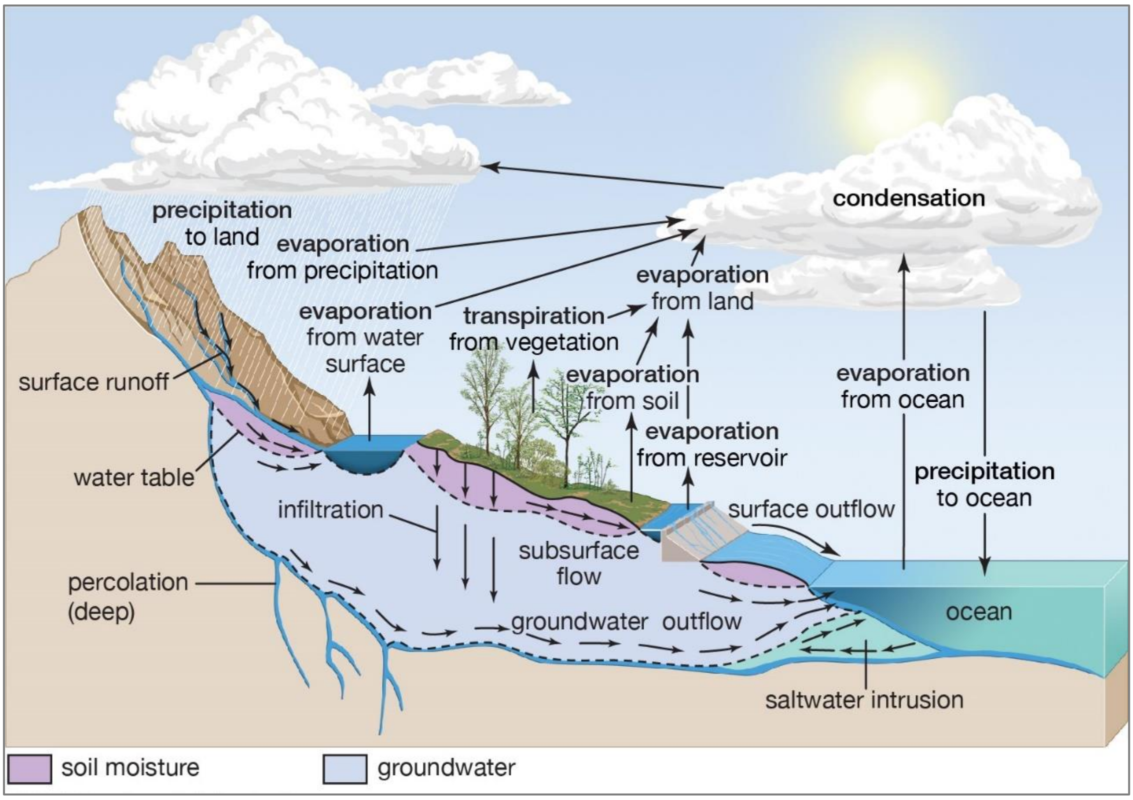

Figure 2.1: The hydrological cycle (Source: Encyclopaedia Britannica 2015).

2.1.2 Water Budget

Overall, the forces that govern the hydrological cycle can be quantified by a concept known as the water budget (Gregory *et al.* 2009; Bethea 2011). The theory behind it essentially states that water flowing into the hydrological system of an area is equal to the water stored in the system and the water leaving that system (see Figure 2.2) (Munn 2002; Gregory *et al.* 2009; California Department of Water Resources 2020). The area, in this case, can be considered as a river catchment, and the amount of water flowing to and from the catchment can be expressed by Equation 2.1 below which is commonly known as the water balance equation (Munn 2002; Bethea 2011; Gregory *et al.* 2009). The water budget and water balance equation are important concepts in water resources management as they aid in the understanding of hydrological phenomena and the development of hydrological models.

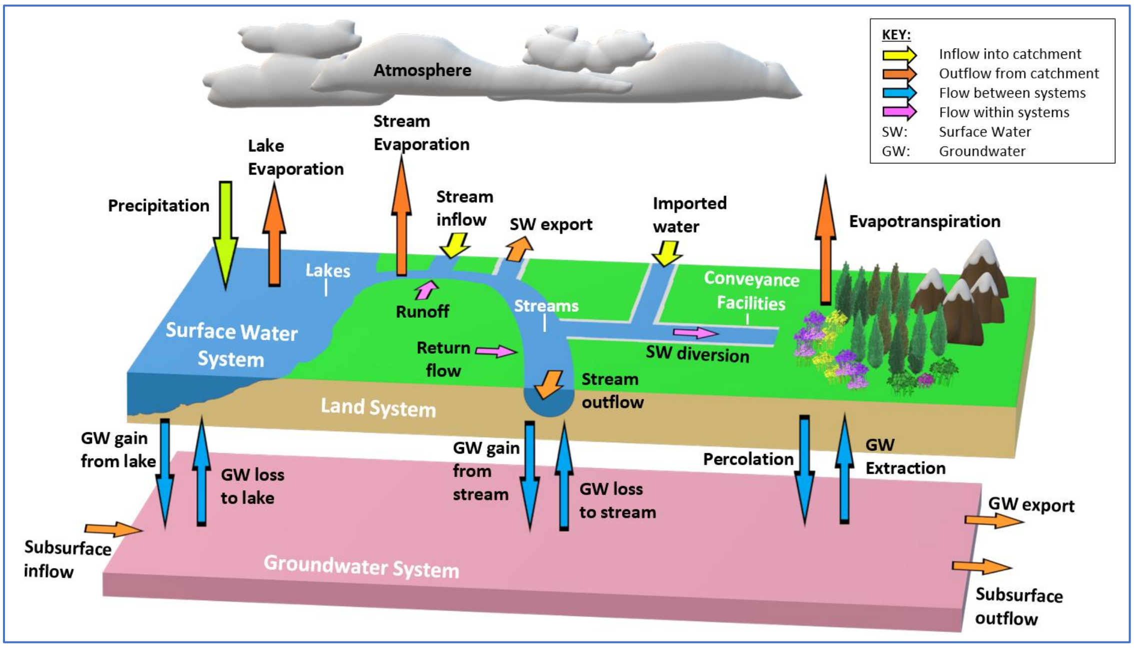

Figure 2.2: Water budget schematic.

$$\Delta S = P + Q_{in} - ET - R \quad \text{………………..} \textbf{ Equation 2.1}$$

Where ΔS is the change in storage (i.e. in subsurface or groundwater), P is precipitation, Q_{in} is water flowing into an area, ET is evaporation, and R is runoff from the area.

2.1.3 Relation of Land Cover to the Hydrological Cycle

Physical features covering a land surface, such as soil, vegetation, buildings, and water, among others, can affect the movement of water within the hydrological cycle (Geremew 2013; Wangpimool *et al.* 2013; Ngeno 2016; Welde & Gebremariam 2017; Abe 2018). This occurs as a result of the features interacting with one or more processes in the hydrological cycle in several ways. The presence of vegetation on a land surface, for instance, can reduce the amount of precipitation reaching the soil through interception and thereby reduce runoff and streamflow in a catchment (Gerrits 2010; Geremew 2013; Abe 2018). Indeed, the amount of interception that occurs may depend on land cover and precipitation characteristics, but it can amount to between 15 to 50 percent of precipitation in a given area (Gerrits 2010).

Generally, a decrease in natural vegetative cover leads to an increase in runoff and streamflow in a catchment since less water is intercepted or infiltrates into the soil after precipitation (Gerrits 2010; Mbano *et al.* 2009; Palamuleni *et al*. 2011; Yao *et al*. 2012). Ngeno (2016) for instance, revealed that a 9.4% loss of forest cover and an increase in agricultural activities over 15 years (1995-2010) in the Nyangores sub-catchment in Kenya caused a 3% increase in streamflow from the whole sub-catchment. Another study by Abe (2018) reported a 2.8% increase in river flow in the Crepori River Basin in northern Brazil due to the conversion of 3.57% of forested area to pasture and bare land.

The effect of LULCC on streamflow often exhibits seasonal variations most apparent between the wet and dry seasons (Guo, Hu & Jiang 2008; Geremew 2013; Sibande *et al*.

2020). Geremew (2013) for example reported a 4.5% increase and a 1.69% decrease in streamflow during the wet and dry seasons, respectively, in the Lake Tana basin in Ethiopia as a result of LULCC. This can be attributed to the change in number and intensity of precipitation events between seasons and how these variations ultimately interact with the changing land cover (Guo *et al*. 2008). For example, an increase in impervious surfaces such as roads or buildings in a catchment may increase streamflow during the wet season since there is more runoff. However, the resulting lack of infiltration during the wet season also means there is less groundwater available to replenish rivers during the dry season, thus causing reduced streamflow. Additionally, Huxman *et al*. 2005 argues that changes in vegetative cover types in an area, from grassland to woody plants for example, can affect the evaporation and transpiration rates in an area. This is as a result of, among other things, changes in relative leaf breadth, stem size, and rooting depth which can translate to seasonal changes in near surface evaporation, water uptake rates by the plants, and transpiration (Huxman *et al*. 2005).

2.2 Land Use/Cover Change

Land use and land cover change (LULCC), also known as land change, is a process through which the surface features of a landscape are transformed (Paul & Harun 2017). It is commonly grouped into two broad categories: conversion and modification (Meyer & Turner 1994; Briassoulis 2009). Conversion refers to a change from one cover or use category to another (e.g. from forest to grassland). Modification, on the other hand, represents a change within one land use or land cover category (e.g. from rain-fed cultivated area to irrigated cultivated area) due to changes in its physical or functional attributes (Meyer & Turner 1994; Briassoulis 2009).

2.2.1 Drivers of Land Use/Cover Change

Neither population nor poverty alone describe the major underlying causes of global LULCC. The driving forces are rather complex since they operate on multiple interrelated spatial-temporal levels (Lambin & Geist 2006; Briassoulis 2009; Ostwald, Wibeck & Stridbeck 2009). The major forces can, however, mostly be summarised by four main categories, namely: natural or environmental, economic, demographic, and institutional (Meyer & Turner 1994; Lambin & Geist 2006; Briassoulis 2009; Ostwald *et al*. 2009).

Natural or environmental forces refer to land cover changes that occur naturally including climate change, and natural disasters such as volcanic eruptions, landslides, and cyclones **(**Meyer & Turner 1994; Lambin & Geist 2006; Ostwald *et al.* 2009**)**. These forces are virtually random and thus are difficult to predict and control. Conversely, the other three forces are all anthropogenic, and hence can be more easily controlled by human intervention.

Economic forces influence how land resources are used based on the market forces of supply and demand (Lambin & Geist 2006; Ostwald *et al*. 2009). For instance, a parcel of land near and easily accessible to a marketplace, may persuade land owners to use the land for the production of goods such as commercial crops as opposed to using the land for forestry or settlement. Demographic traits of a population such as size of the household, age and gender of household members, education, employment status, and personal traits can also collectively interact in various ways to influence LULCC (Lambin & Geist 2006; Briassoulis 2009; Verburg *et al*. 2004). An educated, employed, single woman, for instance, may have different priorities and alternative uses for land as compared to an illiterate, unemployed, married man.

Institutional forces refer to institutional norms (i.e. political, legal, or cultural) that ultimately define how land resources are allocated or used by a population (Meyer &

Turner 1994; Lambin & Geist 2006). Examples of such institutions in Malawi include government land or environmental policies, court rulings, and village development committees (VDCs). Both strong and weak institutions and enforcement of their decisions can contribute to LULCC (Meyer & Turner 1994; Lambin & Geist 2006). This is exemplified in Brazil for instance where illegal mining and logging, linked to corruption, has contributed to deforestation in the Amazon forest (Le Tourneau 2016; Brancalion *et al*. 2018). Since this study sought to establish ways in which decision-makers can convert land use, it focused mostly on the institutional forces.

2.2.2 Application of Remote Sensing in LULCC

A common approach used in land cover studies is the use of remote sensing technologies, specifically land cover mapping. This is a broad field of remote sensing tools and practices used to detect and characterize the bio-physical cover on the earth's surface (Congalton & Green 2008). It has proved to be a crucial component for decision-makers from various fields to plan, develop, and manage their resources effectively (Butt et al. 2015; Saah *et al.* 2019). It has been applied in city planning (Ty *et al.* 2016), fire management (Nieman, van Wilgen & Leslie, 2021), and even for extra-terrestrial endeavours on Mars (Olson *et al*. 2007).

Land cover mapping typically involves classification of remote sensing imagery which aims to identify the type of land cover captured in the image (Canty 2011; Prasad, *et al.* 2015; Andualem, Belay & Guadie 2018). This procedure includes several steps each of varying complexity depending on the study (Canty 2011; Prasad *et al*. 2015). It begins with the identification of a suitable classification algorithm, selection of training samples, image processing and extraction of its features, application of an appropriate classification method, and lastly, optionally, post-classification (Canty 2011; Prasad *et al*. 2015; Wulder *et al.* 2018).

Many approaches for remote sensing image classification have been used in land cover mapping exercises around the world with varying degrees of success (Afanasyev *et al.* 2014; Prasad *et al*. 2015; Wulder *et al.* 2018). Palamuleni (2009), and Sibande *et al.* (2020) for example each applied image classification techniques to analyse freely available satellite data provided by the United States Geological Survey and produced land cover maps later used in hydrological models. Both studies each produced high image classification accuracies exceeding 80% comparable to those produced from premium high resolution data (Mutuku *et al.* 2009; Zhao, Du & Emery 2017). These accuracies were determined using an evaluation technique known as accuracy assessment which estimates how accurately land cover types identified in imagery reflect the reality on the ground (Congalton & Green 2008; Campbell & Wynne 2011; Prasad *et al*. 2015). It involves gathering of ground-true data on land cover or use, and comparing this to a created land cover map (Congalton & Green 2008; Foody 2009; Prasad *et al*. 2015). No consensus exists on what percentage of accuracy is considered good or adequate, hence acceptable values of accuracy are entirely dependent on the researcher and the purpose for which a classification exercise is being conducted (Foody 2002; Muzein *et al*. 2006; Shao & Wu 2008; Prasad & Sahoo 2019).

Accuracy assessment results are determined by many factors including, selection of training samples, as well as the quality of remote sensing data, classification approaches, and image processing techniques used (Lu & Weng 2007; Prasad *et al*. 2015; Maxwell, Warner & Fang 2018). In general, the use of high-resolution imagery coupled with appropriate image processing and advanced classification approaches (such as machine-learning classification) tends to yield the highest accuracy values which can exceed 95 % (Prasad, *et al*. 2015; Shao & Wu 2008; Maxwell *et al.* 2018). However, the most appropriate combination of tools and methodologies varies depending on several factors including the study location characteristics and research requirements, among other things (Lu & Weng 2007; Prasad *et al*. 2015; Maxwell *et al.* 2018). Proper consideration of these factors is therefore imperative.

2.3 Land Use and Streamflow Modification

Several previous attempts around the world have been made to identify ways in which land use can be manipulated to modify streamflow regimes for the benefit of their catchment's inhabitants (Yeo & Guldmann 2006; Evelyn 2009; Owji *et al.* 2012; Zhang *et al.* 2014; Yini *et al*. 2016; Tajbakhsh *et al.* 2018). This manipulation, referred to here as re-patterning, denotes the conversion or reconfiguration of land uses in an area's land use pattern to achieve a new pattern that serves a specific purpose.

Many of the aforementioned attempts at land use or cover (LUC) re-patterning were not only successful but theoretically proved reconfiguration of land uses can have significant positive effects on the catchments studied. Zhang *et al.* (2014) for example studied the Yong-Ding watershed in western Beijing, China using regression, land use, and hydrological modelling. The study showed that optimisation of land use patterns in the watershed between 1993 and 2030 would cause significant reductions in peak flow and runoff volumes (12.35–25.63% and 11.2–22.87%, respectively) as compared to a "business-as-usual" land use scenario in the same period. Table 2.1 summarises the results of this and other similar studies and shows the overall change in quantities, such as runoff, that affect streamflow regime. They suggest that LUC re-patterning could indeed help to reduce peak flows and thus mitigate flood problems in small catchments such as that of the Lilongwe River.

One thing common to all the aforementioned studies however, is that they mostly consider only one extreme of streamflow fluctuation, that is, either peak flows or low flows. They do not consider measures to mitigate both high and low flows despite the aforementioned evidence that the effects of land use changes are usually seasonal. This may therefore present an opportunity missed.

Table 2.1: Summary of results of studies on land use optimization in relation to runoff and streamflow.

STUDY	LOCATION	KEY FINDINGS	REFERENCE
Utilizing geographic information system (GIS) to determine optimum forest cover for minimizing runoff in a degraded watershed	Rio Minho watershed, Jamaica	Runoff: -5 to -24%	Evelyn 2009
Integration of linear programming and a watershed-scale hydrologic model for proposing an optimized land-use plan and assessing its impact on soil conservation	Nagwan watershed, Jharkhand, India	Sediment load: -14.61%	Kaur *et al.* 2004
Watershed modelling for sustainable land use planning	Langat basin, Malaysia	Runoff: -2.76%; Sediment load: -27.48%	Memarian 2016
Minimizing surface runoff by optimizing land use management	Jajrood watershed, Tehran province, Iran	Runoff: -36.70 to 73.03%	Owji *et al.* 2012
A GIS-based integrative approach for land use optimization in a semi-arid watershed	Bayg watershed, Iran	Runoff: +22%; Sediment load: -16.78%	Tajbakhsh *et al.* 2018
Optimization of land use pattern reduces surface runoff and sediment loss	Hilly-Gully watershed, Loess Plateau, China	Runoff: -2.7% to -17.6%	Yini *et al.* 2016
Land-use optimization for controlling peak flow discharge and nonpoint source water pollution	Old Woman Creek watershed, Ohio, USA	Peak flow: -44%	Yeo & Guldmann 2006
Grid-based land-use composition and configuration optimization for watershed storm water management	Yong-Ding watershed, Beijing, China,	Peak flow: -12.35 to -25.63%; Runoff: -11.2 to -22.87%	Zhang *et al.* 2014

2.4 Conceptual Framework

This review has so far shown that LULCC can predictably influence streamflow and such dynamics can be easily studied using a modelling approach. These concepts are presented in Figure 2.3 which illustrates the relationship between land use and its driving forces (in orange), and highlights how land use interventions would influence institutional forces to cause LULCC. The framework also depicts the effect of climate on land factors such as vegetation, and ultimately streamflow. Items encapsulated in green dotted lines represent processes through which water moves from one system to the other.

With the framework in mind, the study thus aimed at providing land and water managers in Lilongwe River Catchment with credible information from which to develop pragmatic options for addressing the flood and drought problems affecting the catchment. As such, examination of the current and possible future land use and streamflow scenarios, coupled with an analysis of legal and institutional frameworks in conjunction with consultations with land managers are approaches that were settled for in this study. Malawi government's land and water management paradigms and concerns were also taken into consideration in developing the framework.

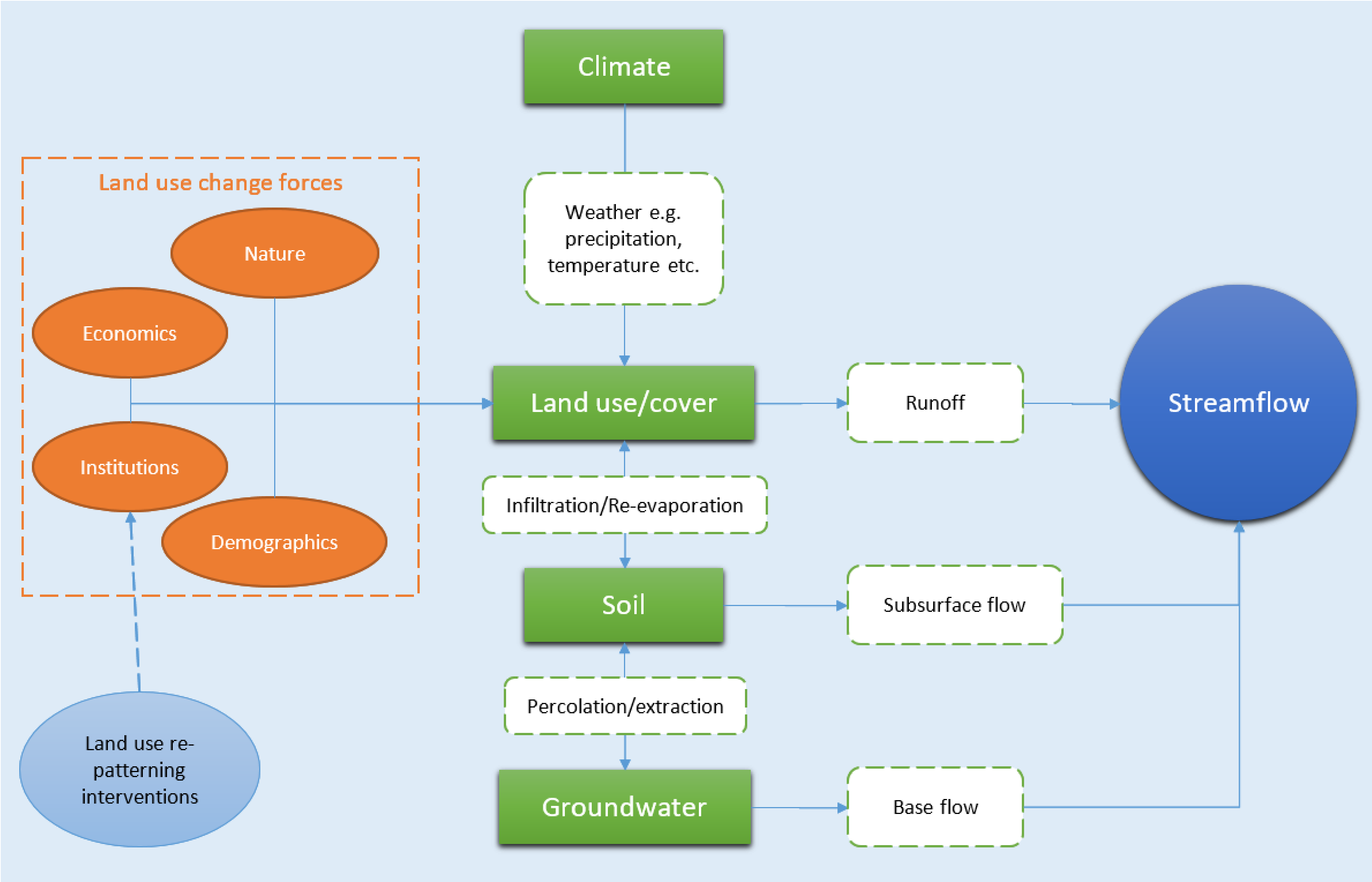

Figure 2.3: Conceptual framework of the study.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Study Area

The study was conducted in the Lilongwe River Catchment which originates from the Dzalanyama Forest in the south western part of Lilongwe district, Malawi. Lilongwe is the capital and most populous district in Malawi with an estimated 2,626,901 inhabitants (NSO 2018). The district is located on a plateau 1,133 meters above sea level at latitude 13° 30′ S, and longitude 33° 37′ E (Msowoya *et al.* 2016). The district is largely known for its gently undulating surface with the most significant slopes occurring in the Dzalanyama mountain range south-west of Lilongwe City.

Lilongwe exhibits a seasonal sub-tropical climate with average temperatures varying between 14.1 to 26.9 ℃ (Malawi Department of Climate Change and Meteorological Services (MDCCMS) 2014). The lowest temperatures are usually experienced between June and August with a mean minimum of 9.3 ℃, whilst the highest temperatures are common between September and November, with a mean maximum of 29.5 ℃ (MDCCMS 2014). The district experiences a short wet season that runs from December to March, and a lengthy dry season that covers much of the remainder of the year (Kaonga, Tenthani & Kosamu 2015; MDCCMS 2014). About 900 mm of rainfall is experienced annually, more than 90 percent of which occurs in the wet season at a rate of about 200 mm per month (MDCCMS 2014).

Malawi is divided into several catchments and sub-catchments as shown in Figure 3.1. The Lilongwe River Catchment covers an estimated area of 1,812 km^2 and originates from the Dzalanyama mountain range in sub-catchment 4D. This sub-catchment in turn forms part of Catchment 4 which is also known as the Linthipe catchment. The Lilongwe River is fed by five main tributaries which are Likuni, Katete, Lisungwe, Nanjiri and Nathenje rivers (Nemus 2015). Small wetland areas (dambos) lie at the source of each of these tributaries and all but the smallest streams in the Dzalanyama area continue to flow throughout the year (Nemus 2015). Nevertheless, two dams were constructed on Lilongwe River, Kamuzu Dam 1 and 2, in 1965 and 1989 respectively to supplement water supply requirements in Lilongwe City (World Bank 2017).

The catchment area is intensively cultivated and hence most of the natural vegetation has been cleared for agriculture (Hranova 2006). However, significant areas of forest are still found in the Dzalanyama Forest Reserve which was established in 1922 (Munthali & Murayama 2011) and lies south-west of the catchment. The reserve covers about 98,934 hectares and forms part of the border with Mozambique (Hranova 2006; Nemus 2015). Most infrastructure developments and commercial activities occur in the city located around the centre of the district.

Special interest was given to the sub-catchment 4D in this study as shown in Figure 3.1 since this is the sub-catchment area through which the Lilongwe River flows and has been gauged for a substantial period (Nemus 2015). The location of the gauging station 4D4 was thus considered the outlet for the catchment. Figure 3.2 shows an outline map of Lilongwe district and the extent of the study watershed. It also shows the rivers in Lilongwe and the river outlet point of the study watershed. Figure 3.3 presents a schematic of the hydrologic system for Lilongwe River, including locations of major water abstractions by different users, and natural hydrological processes.

Figure 3.1: Study area in Lilongwe depicting sub catchment 4D. (Source: Ministry of Forestry and Natural Resources).

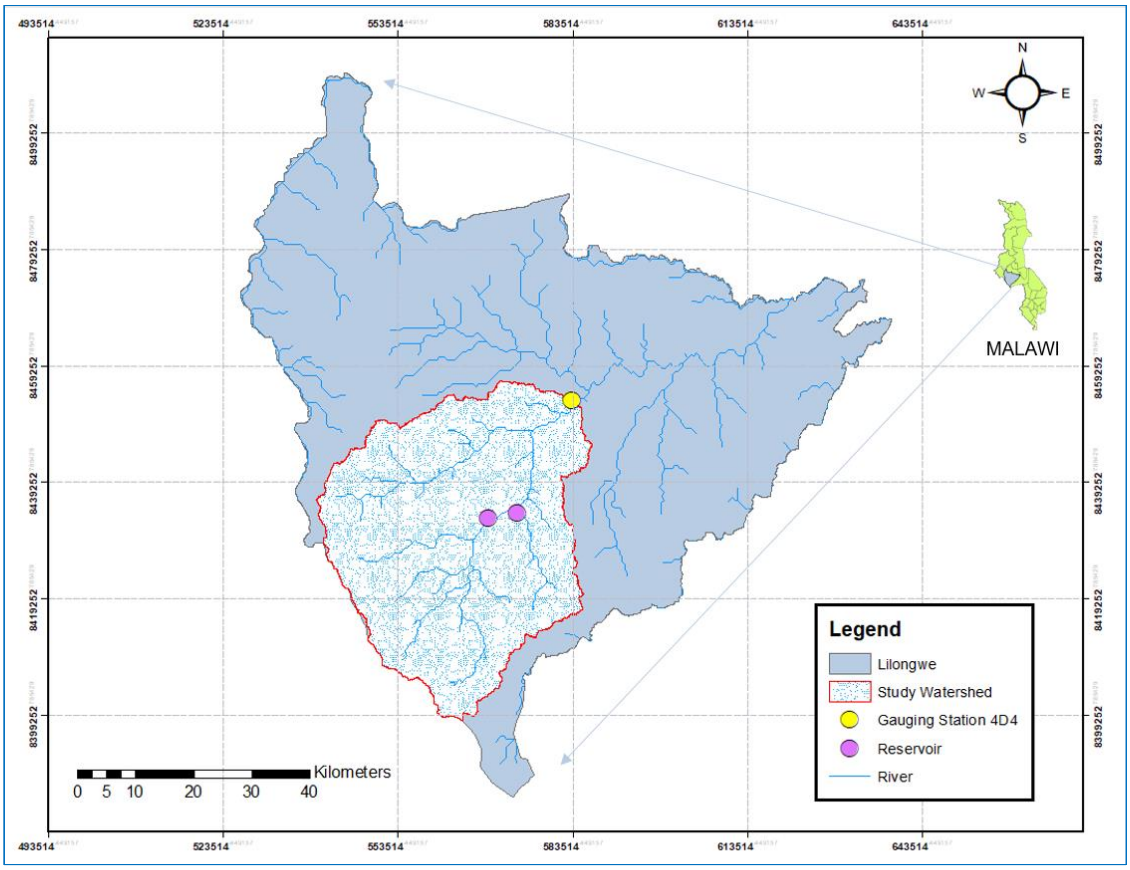

Figure 3.2: Lilongwe district and all its major rivers.

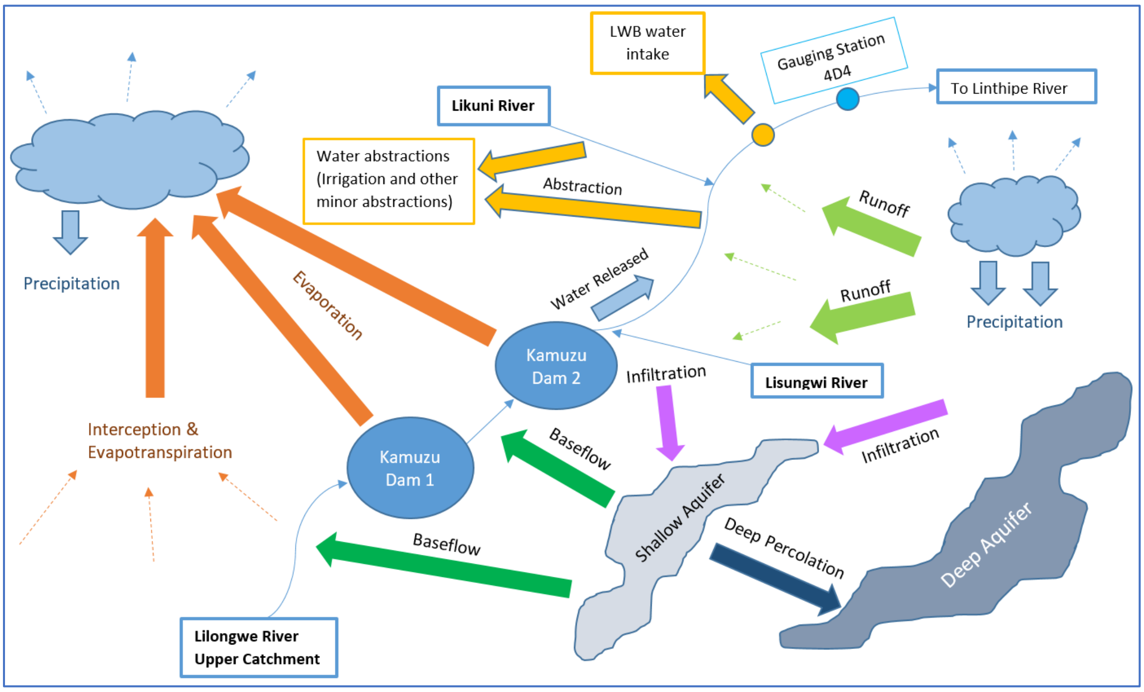

Figure 3.3: Lilongwe River hydrological system schematic.

3.2 Study Design

The study adopted a mixed-methods approach in which the first objective was completed using a cross-sectional survey design, whilst objectives 2 and 3 were achieved using an experimental research design. This approach was used because the problem addressed by this study was qualitative, as evidenced by the research questions, and thus necessitated the use of a qualitative approach. However, since the study also involved the manipulation of variables, that is, land use patterns, it also called for the use of a quantitative experimental design. This enabled the study to gain an understanding of the current streamflow regime by collecting cross-sectional data, and later to develop and test possible future land use and streamflow regime scenarios through iterative experimentation.

The study collected both qualitative and quantitative data from both primary and secondary data sources. Both quantitative and qualitative methods were then used to analyse the data.

3.3 Projected Lilongwe River Flow Regime Based on Current Land Cover Pattern in the Catchment

3.3.1 Data Collection

3.3.1.1 Satellite Imagery and Elevation Data

A cross-sectional research design approach was used to collect qualitative secondary data. Satellite imagery of the study area captured in 1979 by the Landsat 2 satellite, and in 2019 by the Landsat 8 Operational Land Imager (OLI) satellite was obtained from the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Centre archive[1]. Images captured during the dry season were specifically selected for use since the scenes were less likely to feature clouds and seasonal vegetative cover which may produce erroneous results after analysis. A Digital Elevation Model (DEM) was also obtained from the USGS-EROS archive to provide elevation data of the study area.

3.3.1.2 Land Cover Referencing Data

Referencing samples of verified land cover types in the study area were required for training and validation of the image classification exercise. Foody (2009) and Jin, Stehman & Mountrakis (2014) explain that the number of training samples required for successful classification of images is very subjective and dependent on the purposes of the research. Ramezan, Warner & Maxwell (2019) further revealed that collecting a few training samples from a small representative subset of a study area yields similar classification accuracy as collecting a large sample dataset from the whole study area. Considering the size of the study area as well as resources that were available to

[1] https://earthexplorer.usgs.gov

conduct the study, a minimum of 30 training samples and 10 validation samples per land cover class were considered sufficient for successful classification.

The locations of referencing sites were identified through simple random sampling with the aid of the Random Point Generator tool in ArcGIS 10.4. A field survey was then conducted which first identified a sizeable patch (at least $15m^2$) of the dominant land cover type in the area, and then recorded its coordinates using a Global Positioning System (GPS) device. High-resolution Google Earth images were later used to collect referencing data in parts of the catchment that were inaccessible as has been proven effective by other studies (Hu *et al*. 2013; Tilahun & Teferie 2015; Phan, Kuch & Lehnert 2020).

Referencing data points used in accuracy assessment were later identified through disproportionate stratified random sampling as recommended by Ramezan *et al.* (2019). This method not only reduced sample requirements, but also ensured an adequate number of samples were collected to validate the classification of rare land cover types. The referencing points were generated using the Create Accuracy Assessment Points tool in ArcGIS 10.4 and land cover at each location was verified through a site visit or using Google Earth for inaccessible areas.

A combined total of 500 reference points was collected in the catchment in which 7 land cover classes were identified through field observations and with the aid of literature documenting land cover in the area (Food and Agriculture Organization of the United Nations, 2012). These classes were Forest, Water, Wetland, Grassland, Cropland, Bare land, and Settlements. Table 3.1 below breaks down the number of points collected for each class.

Table 3.1: Land cover referencing data collected in the study area.

Land Cover Type	Number of Samples Collected		
	Field Survey	**Google Earth**	**Total**
Forest	31	85	116
Water	20	30	50
Wetland	23	48	71
Grassland	13	26	39
Cropland	45	86	131
Settlement	15	38	53
Bare land	18	22	40
TOTAL	**165**	**335**	**500**

3.3.1.3 Climate Data

The study collected both historical and future weather data to run a hydrological model known as the Soil Water Assessment Tool (SWAT). This model requires an input of precipitation, maximum and minimum temperature, wind speed, solar radiation, and relative humidity data sets. Historical records of this data from 1950 to 2019 were obtained from the Malawi Department of Climate Change and Meteorological Services (MDCCMS). This data was recorded at four different meteorological stations namely: Chitedze, Sinyala, Kamuzu Dam, and Dzalanyama-Katete. The four stations all had records of precipitation data, but only Chitedze had records of temperature and wind speed data. Solar radiation and relative humidity data were not available in usable quantities from any of the stations. As a result, the SWAT model was used to simulate this data based on average weather conditions recorded between 1970 and 2001 by satellites. This data was obtained from the National Centres for Environmental Prediction (NCEP) online archive[2].

Climate models were used to project the future weather data used in this study. Warnatzsch and Reay (2018) conducted a study assessing the ability of different climate models in modelling climate in Malawi based on historical records. The study concluded that regional climate models (RCMs) often outperformed global circulation models (GCMs) in replicating climate conditions in Malawi due to their scaled-down nature but this outcome is mainly dependent on the boundary conditions the RCM was based on. Four of the best-performing RCMs identified in that study were selected to be used in projecting climatic conditions in this study. Based on the name of the GCM driving them, and the organisations which developed them, the selected models are commonly abbreviated as: CLMcom-CCLM4-8-17, SMHI-RCA4, and MPI-CSC-REMO2009, and CCCma-CanRCM4. The first 3 models were obtained from the Earth System Grid Federation (ESGF) online database[3], and the latter was obtained from the Canadian Centre for Climate Modelling and Analysis online database[4]. All model data obtained was based on the low emissions Representative Concentration Pathway 4.5 (RCP4.5) scenario which is one of four trajectories of greenhouse gas concentrations adopted by the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change 2014). As with the historical data, only precipitation, temperature, and wind speed data were available from all 4 models and all other weather data was simulated by SWAT.

The obtained climate model data is stored in a special multidimensional array format known as NetCDF which was specifically designed to contain climate data (Rew &

[2] https://globalweather.tamu.edu
[3] https://esgf-node.llnl.gov/projects/esgf-llnl/
[4] https://climate-modelling.canada.ca/climatemodeldata/canrcm/CanRCM4/AFR-44_CCCma-CanESM2_rcp45/index.shtml

Davis, 1990). No open-source programs were available to the study for extraction of data from the hundreds of files obtained in this format. A simple program was thus created by the researcher in the Python programming language in order to extract the weather data for the study area from the NetCDF files and save it in a Microsoft Office Excel 2016 workbook for easy manipulation. The Python script may be accessed from the following GitHub repository: https://github.com/csibande/netcdf-to-excel.

3.3.1.4 Topographic Data

A 90 m x 90 m Digital Elevation Model (DEM) raster image was obtained from the USGS online database to serve as topographic data for the model (Jarvis *et al.* 2008). This raster was captured by the Shuttle Radar Topography Mission (SRTM) and was used in this study to aid in the delineation of sub-basins in the watershed.

3.3.1.5 Soil Data

Soil data was also necessary for modelling the hydrology of the catchment. This data was extracted from a global soil map obtained from the Food and Agriculture Organisation (FAO) archive (FAO, 2007). This soil map only displays three major soil types within the study watershed because of its low resolution, however, similar studies have shown that it is sufficiently accurate for the purposes of this study (Daggupati *et al*. 2018; Kangsabanik & Murmu 2017).

3.3.1.6 Streamflow Data

Daily streamflow data of the Lilongwe River was obtained from the Ministry of Agriculture, Irrigation, and Water Development (MAIWD). This data was recorded at station 4D4 on the river and captured data from 1957 to 1998. However large data gaps are present throughout the record, especially between 1982 and 1983, and between 1992 and 1998.

3.3.1.7 Reservoir Data

Kamuzu Dam 1 and 2 were constructed over the Lilongwe River in 1965 and 1989 respectively which resulted in alteration of the natural flow of the river. It was therefore vital that the SWAT model account for the presence of the dams in the flow output. Dam parameters such as height of the spillways, and the first date of operation were extracted from reports provided by Lilongwe Water Board (LWB) (LWB 2001; LWB 2013).

3.3.2 Data Processing and Analysis

3.3.2.1 Current Land Cover

3.3.2.1.1 Image Correction

Raw satellite imagery often possesses several radiometric, atmospheric, and geometric flaws. These are caused by the curved shape of the Earth, interference by airborne molecules in the atmosphere, daily and seasonal variations in the amount of solar radiation received at the surface, and imperfections in scanning instruments among other things (Kuusk & Paas 2007; Patel & Thakkar 2016; Hadjimitsis *et al.* 2010). To rectify these issues, the satellite imagery had to undergo a series of image correction techniques to ensure an accurate representation of reality was depicted in the images.

The atmospheric and topographic correction (ATCOR) model in PCI Geomatica 2018 software (Richter & Schlapfer 2016) was used to correct radiometric, atmospheric, and geometric distortions in the 2019 Landsat 8 OLI images to improve the accuracy of the resulting land cover maps. The model was calibrated using coefficients provided in the metadata files that accompany the satellite imagery. However, no image correction techniques could be used for the 1979 Landsat 2 images as no tools that support correction for this version of sensor were available to the study.

3.3.2.1.2 Image Classification

Image classification was conducted on the corrected images to identify the types of land cover in the study area. Several methods for achieving this exist based on either the use of pixels or objects in an imagery scene and are each relevant in different applications (Lillesand, Kiefer & Chipman 2011). One method that has gained popularity in recent times is the machine learning approach known as Support Vector Machines (SVMs) which has in many cases proved more effective than many other approaches in land cover mapping (Pal & Mather 2005; Hussain *et al*. 2013; Gu *et al.* 2015). In addition to using small training datasets, the SVMs algorithm is also able to use non-normally distributed training data for classifying remotely sensed imagery. It is thus easy to work with (Foody *et al.* 2016), and maintains high overall classification accuracy (Foody & Mathur 2004). Furthermore, Maxwell *et al*. (2018) stipulate that accurate referencing data used to train the algorithm is the main key to effective use of the SVM approach.

Supervised image classification was thus carried out on the 1979 and 2019 corrected Landsat images using the SVM algorithm in ArcGIS 10.4. The classification process used 60% of the land cover reference data obtained (300 samples), while the other 40% (200 samples) was later used to assess the accuracy of the classified maps as demonstrated by Gilbertson, Kemp & van Niekerk (2017). No secondary data sources were available to the study to create ground truth data representative of the 1979 land cover in the study area. As such, the classification of the 1979 images relied solely on historical classifications or descriptions of the area (FAO 2012), and the researcher's familiarity with the area.

Due to the spectral similarities of the 7 land cover classes identified and the seasonal changes they undergo, many parts of the classified land cover map were suspected of misclassification. For instance, during the rainy season, wetlands distinctly discernible by the presence of healthy wetland vegetation such as reeds and water hyacinth resembled dry grasslands during the dry season at which time the acquired satellite images were captured. To resolve the challenge, wetlands and grasslands were combined into one class to prevent excessive classification errors. Dusty roofs of buildings and other infrastructure were also spectrally similar to bare land and so the settlement class was combined with the bare land class. The classified images were then reclassified using ArcGIS tools to make a total of 6 land cover classes in the study area. The exercise thus produced two land cover maps for the study area, one for 1979 and the other for 2019.

3.3.2.1.3 Accuracy Assessment

Using 40% of the ground truth samples collected, the study calculated the accuracy of the 2019 land cover map produced using a confusion matrix and some of its related statistics (Foody 2002; Congalton & Green 2009; Prasad *et al.* 2015). These statistics are the Overall Accuracy (OA), Kappa Coefficient (KC), Producer's Accuracy (PA), User's Accuracy (UA), and the Errors of Omission (EO) and Commission (EC).

The OA measures the proportion of pixels correctly classified by the system while the KC is an unbiased statistic that measures how well the classification process performed as compared to just randomly assigning land cover classes to classified values (Parece & Campbell 2013). Congalton and Green (2009) explain that KC values exceeding 80% represent very good classification performance, while those between 40% to 80% represent moderate performance, and those below 40% signify poor performance. The EC measures the probability that a reference sample was wrongly mapped into a land cover class, whereas the EO measures the probability that a reference sample was wrongly excluded from a land cover class. The PA and UA refer to the probabilities that reference samples were correctly categorized into a particular class after removing the EO and EC respectively (Lillesand *et al.* 2008).

3.3.2.2 Climate Projections

Model outputs are only as good as the assumptions they are based on (Berro 2018). Considering the complexity of the natural world, it is virtually impossible for any climate model to accurately assume all empirical conditions governing weather conditions in any area (Räisänen 2007; Betz 2015). To mitigate this problem, many studies recommend the use of ensemble data, which is the average output of several different models at each data point (Knutti *et al*. 2010; Semenov & Stratonovitch 2010; Warnatzsch & Reay 2018). Warnatzsch and Reay (2018) for instance revealed that ensemble data could satisfactorily replicate historical temperature data in Malawi and would likely do the same for future temperature projections. However, the study also revealed that ensemble data could not satisfactorily replicate the observed precipitation data. As a result, the paper recommended the use of multiple models individually to simulate precipitation.

While ensemble data is essential to understanding the average trends of climatic variables, it suffers a major disadvantage in that it cannot capture extreme events. This is because unless the same extreme weather conditions were predicted to occur on the same days in all models, the ensemble output would register suppressed average values for those events. As a result, the ensemble output would be unrealistically devoid of almost any extreme weather events. Due to the nature of this study and the importance of capturing the effect of extreme weather conditions such as heavy rain, on streamflow, the ensemble approach was considered unfit for this study. Instead, the study used output data from each of the four aforementioned selected RCMs separately.

Analysis of the direction and significance of temporal trends in climatic variables was performed on the combined data from the observed climate record (1990 to 2019) and each RCM scenario (2020 to 2049). This was done by applying the Mann-Kendall test (Mann 1945; Kendall 1975) and the Sen Slope Estimation test tools in XLSTAT 2016 on annual precipitation, minimum and maximum temperature datasets. All observed data used for this analysis was recorded at Chitedze Meteorological Station as it was the most complete in the 1990 to 2019 period.

The Mann-Kendall (MK) is a non-parametric, rank based statistic widely used and recommended for detecting monotonic trends in hydro-meteorological time series data (Machiwal & Jha 2012; Panda & Sahu 2019; Nkhoma *et al*. 2020). It was selected for this analysis due to its nonparametric nature, which removes the need for input data to be normally distributed.

Given a time series x_t where time $t = 1, 2, \ldots n$, each data point (x_t) in the series is compared with all subsequent values (x_{t+1}) to create a new series z_k as follows (Machiwal & Jha 2012):

$$z_k = 1 \quad if \;\; x_t > \; x_{t`}$$

$$z_k = 0 \quad if \;\; x_t > \; x_{t`}$$

$$z_k = -1 \quad if \;\; x_t > \; x_{t`}$$

where $k = (t` - 1)(2n - t`)/2 + (t - t`)$.

The MK statistic (S) is then calculated as given in Equation 3.1 (Machiwal & Jha 2012).

$$S = \sum_{t`=1}^{n-1} \sum_{t=t`+1}^{n} z_k \qquad \text{……………..…..... Equation 3.1}$$

The sign of the MK statistic defines the direction of trend, while the z-statistic is used to determine the statistical significance of the trend (Panda & Sahu 2019). The magnitude of the trend established by the MK test can then be quantified using another nonparametric method known as Sen's Estimator (Sen 1968) given in Equation 3.2.

$$\beta = Median\left(\frac{x_i - x_j}{i - j}\right) \qquad for\ all\ i < j \qquad \text{………………… Equation 3.2}$$

where β is the slope between data points x_i and x_j, and $x_i\ and\ x_j$ are data measured at time i and j respectively.

3.3.2.3 Flow Regime Projections

3.3.2.3.1 Introduction to the Soil Water Assessment Tool

Projecting the flow regime of Lilongwe River required the use of a hydrological model to simulate various physical processes occurring in the catchment, and to produce reliable outputs based on the projected input data. The model selected for this purpose was the Soil Water Assessment Tool (SWAT). This is a semi-distributed physically-based hydrological model designed to simulate the impacts of alternative management decisions on hydrological processes in watersheds with varying spatial conditions and over long periods (Arnold *et al.* 2012). It was selected for this study as its deterministic nature allowed for the conclusive comparison of the hydrological effects of different land use scenarios alone in the Lilongwe River Catchment. Being semi-distributed, the model has relatively minimal data requirements which facilitated the conduction of this study in a data-scarce area. The model was also selected because it is open-source and has been successfully used across the world (Douglas-Mankin, Srinivasan & Arnold 2010; Arnold *et al.* 2012; Gassman *et al.* 2014) including in sub-tropical climates such as Malawi. For this study, the ArcGIS integrated interface for the SWAT model known as ArcSWAT version 2012.10_4.19 was used.

3.3.2.3.2 Model Setup

SWAT requires topographic, land cover, soil, weather, and if any, reservoir data to setup. Recorded (1950-2019) and projected (2020-2049) weather data were combined into one data set and prepared in Comma Separated Value format as recommended by the ArcSWAT manual (Winchell *et al.* 2013). Reservoir parameters used for configuration assumed the dams aimed to hold as much water as possible since they are mainly used for water supply. The model was therefore set up to release water from the principal spillway at a specified release rate only when the desired full volume is reached, or from the emergency spillway in times of excessive inflow.

With the data specified above the model was run on a daily time-step to simulate streamflow between 1950 and 2049, with the first 4 years of simulation output configured to be skipped to allow for initialization of the model. The initial run of the model was set up with the 1979 land cover map produced earlier to replicate as closely as possible conditions during the model calibration and validation period selected (1954-1964). The model was then set up and run again after calibration and validation using the 2019 land cover map produced earlier to project the river's flow regime.

3.3.2.3.3 Calibration and Validation

This study adopted a similar approach to that of LWB (2013) by calibrating the SWAT model using daily data recorded before the construction of the Kamuzu Dams which altered the natural flow of the stream. Calibration was thus performed using data from 1954 to 1960, and validation with data from 1961 to 1964. This was carried out using an auto-calibration software known as SWAT-CUP version 5.1.5.4, a program designed to integrate various calibration and uncertainty analysis programs specifically for the

SWAT model (Abbaspour 2013). The Sequential Uncertainty Fitting version 2 (SUFI2) calibration and uncertainty program in SWAT-CUP was used for calibration and validation of the model. With the use of literature (Abbaspour 2015; Abbaspour 2018), and expert judgement, a total of 15 hydrological parameters relevant to the catchment and those that improved the performance of the model were iteratively selected and calibrated.

Two statistical parameters commonly used to assess the calibration and validation performance of a model were used for this study. These are the Nash-Sutcliffe Efficiency coefficient (NSE) and the coefficient of determination (R^2) (McCuen *et al.* 2006). Moriasi *et al.* (2007) report that based on performance ratings from several studies, the acceptable NSE values for both calibration and validation are Satisfactory if NSE > 0.5; Adequate if NSE is between 0.54 and 0.65; or Very Good if NSE > 0.65. Moriasi *et al.* (2007) and Santhi *et al.* (2001) also report that for R^2, values greater than 0.6 indicate good model performance for both calibration and validation. Table 3.2 lists the parameters and the respective value ranges used.

Table 3.2: Hydrologic parameters used for calibration and validation of SWAT.

Parameter	Description	Min Value	Max Value
CH_COV1.rte	Channel erodibility factor.	0.199	0.357
CH_COV2.rte	Channel cover factor.	0.298	0.639
CH_D.rte	Average depth of main channel	0.602	0.998
CH_N2.rte	Manning's "n" value for the main channel.	-0.018	0.155
CH_S2.rte	Average slope of main channel.	0.846	1.387
CN2.mgt	Soil Conservation Service runoff curve number f.	-23.889	-15.383
ESCO.hru	Soil evaporation compensation factor.	2.043	2.621
GW_DELAY.gw	Groundwater delay (days)	-72.240	-52.231

GW_QMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm).	2009.905	2866.605
GW_REVAP.gw	Groundwater re-evaporation coefficient.	-0.140	0.175
RCHRG_DP.gw	Deep aquifer percolation fraction.	4.082	4.945
RES_RR.res	Reservoir average daily principal spillway release rate.	0.208	0.389
REVAPMN.gw	Threshold depth of water in the shallow aquifer for re-evaporation to occur (mm).	74.218	86.021
SHALLST.gw	Initial depth of water in the shallow aquifer (mm).	-667.594	-396.710
SOL_AWC().sol	Available water capacity of the soil layer.	1.866	3.582

3.3.2.3.4 Flow Regime Projection

Data from each Regional Climate Model (RCM) was entered into the calibrated SWAT model. The model was then executed without any further parameter changes. Since SWAT is deterministic, the output of the model was a direct reflection of the RCM data input. These outputs were then compared to the observed streamflow records. To aid in the interpretation of outputs, a flood frequency curve was derived from the records using Weibull's formula given in Equation 3.3 (Şen 2017).

$$Return\ Period = \frac{Number\ of\ years\ in\ record + 1}{Magnitude\ rank\ of\ data\ point}$$ .... **Equation 3.3**

Due to the prevalence of large data gaps in the streamflow record however, especially from 1992 to date, comparisons could only be made using data from before 1992. This posed a significant challenge considering many changes to the catchment and river itself occurred during the recording of this data, including the upgrading of Kamuzu Dam 2. Gaps in the record were handled by simply excluding problematic data points from analysis. Specifically, data from October 1982 to June 1983, and all data from 1992 to date was unavailable. All other gaps in the data were handled though interpolation, or were deemed insignificant as they lasted no more than a few days and since the flow data was analysed on monthly or yearly basis. All in all, the data provided an important benchmark to evaluate the effect of the different projected climate scenarios.

3.4 Proposing Practical Land Use Patterns for the Lilongwe River Catchment Based on the Ideal Streamflow Requirements

3.4.1 Data Collection

This objective adopted an experimental approach and collected both primary and secondary qualitative and quantitative data.

3.4.1.1 Water Abstraction Data

Water abstraction data from licensed abstractors operating on the Lilongwe River was obtained from the Malawi National Water Resources Authority (NWRA). This data included details on the identity of abstractors, location of abstraction, and the quantity of water abstracted. More data detailing water demand from informal users and other beneficiaries of the river was then sourced from LWB.

3.4.1.2 Protected Areas Data

Shapefiles charting the location of protected areas, and roads in the study area were obtained from the Protected Planet[5], and the Humanitarian Data Exchange[6] online archives respectively. These are reputable archives run by United Nations affiliate organisations. Other data used in this objective such as streamflow and land cover data were collected or produced during Objective 1 data collection and data analysis exercises respectively.

3.4.1.3 Land Allocation Legal Restrictions

Two key informant interviews were conducted with Ministry of Land officials with the main aim of informing the study of how land use allocation is conducted in Malawi, and subsequently guide the configuration of the Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) model used in the study. More details on the model are explained

[5] https://www.protectedplanet.net/country/MWI
[6] https://data.humdata.org/dataset/hotosm_mwi_roads

in Section 3.4.2.4.1 below. Specifically, the interviews gathered information on which laws or departmental policies and practices regarding land use planning could be used to create configuration files for Dyna-CLUE that define areas where certain land use changes are prohibited. The interviews were conducted using interview guides and aimed at identifying how legal requirements of different departments are considered during the land use allocation process. The two officials were the Acting Commissioner for Physical Planning and the Principal Estate Management Officer. Government documents on the laws, policies, and manuals governing land use allocation were identified by the informants and obtained from their respective departments.

3.4.1.4 Flood Modelling

Flood modelling of streams in the catchment required river cross-section data which was obtained from LWB, and terrain data which was already obtained in Objective 1 in the form of a DEM. Lastly, the 100-year flood flow determined in Objective 1 was used as peak flow data.

3.4.2 Data Processing and Analysis

Different land use patterns in the Lilongwe River Catchment may affect streamflow differently. Therefore, to understand what LUC re-patterning schemes are possible for the catchment, a set of different land use scenarios had to be developed. These scenarios had to be practical to ensure any findings of the study are applicable to the study area. Practicality in this regard referred to legal, institutional, and socio-economic factors that determined the likelihood of a proposed land use to be realised in the study area. The study, however, assumed the availability of adequate financial resources to perform the transformation of land in the study area since considering Malawi's economic situation, this would be dependent on several unpredictable factors such as political will and donor funding (Booth *et al.* 2006; De & Becker 2015; Page 2019).

3.4.2.1 Effect of Land Cover Classes on Flow

Before LUC re-patterning could be performed, it was important to understand how each land use type may affect streamflow in the catchment. To that end, the sensitivity of streamflow to each land use type identified in the catchment was evaluated. Several factors other than land use or land cover can affect the amount of water reaching a river including soil type, topography, and evaporation. Therefore, the goal of this evaluation was aimed at singling out each land use type as the sole cause of a change in streamflow. This was done by creating 5 homogenous land cover maps featuring only one of each of the land cover types identified in the catchment. This map was then entered into the calibrated SWAT model and run from 2020 to 2049. Streamflow, runoff, infiltration, evapotranspiration, and baseflow outputs were then compared with the output from the current land cover scenario determined in Objective 1. Results were compared on a seasonal basis since studies have shown that land cover effects on streamflow vary depending on the season being analysed (Geremew 2013; Ogden *et al*. 2013**;** Marhaento *et al*. 2018). This allowed the study to determine how each land use type alters streamflow irrespective of other physical factors.

3.4.2.2 Ideal Streamflow Regime Calculation

Environmental flows refer to the streamflow required for the maintenance of riverine ecosystems and form part of the water demanded from the Lilongwe River. This flow was calculated according to NWRA guidelines as the streamflow with a 90% probability of occurrence in the river at any given time (GoM 2014). Projected water demand for the Lilongwe River was then calculated by summing up the daily streamflow required for environmental flows and the 2049 projected daily streamflow required by licensed water abstracters (see Equation 3.4).

$$TWD_{2049} = AQ_{2049} + EQ \quad \text{.................... \textbf{Equation 3.4}}$$

Where TWD_{2049} is the total demand for water from the Lilongwe River in 2049, AQ_{2049} is the projected water demand for abstraction, and EQ is the environmental flow.

NWRA policy prohibits development or cultivation within the 100-year buffer zone of any water course. The 100-year flood flow was hence taken as the minimum flood discharge since decision-makers would not be liable for any flood damage caused as a result of illegal activity. An ideal streamflow value was thus regarded as any discharge value that exists in the range between the minimum flood discharge and the water demand (see Equation 3.5).

$$Q_{100} > Q_{ideal} \geq TWD_{2049} \quad \text{.................... \textbf{Equation 3.5}}$$

Where Q_{100} is the discharge for a flood with a return period of 100 years in Lilongwe River, Q_{ideal} is the ideal streamflow value, and TWD_{2049} is the total demand for water from the Lilongwe River in 2049.

3.4.2.3 Land Use Allocation Guidelines in Malawi

Realistically, LUC re-patterning cannot be implemented in the absence of legal and institutional frameworks as these, among other things, maintain the environmental and socio-economic order in an area. It was, therefore, necessary for any land use scenarios proposed to abide by legal or institutional constraints which guided land use allocation during re-patterning. A list of these constraints was compiled using information obtained from the key informant interviews and thereafter a review of legal publications identified by the key informants. Table 3.3 below presents the list of legal publications reviewed to compile the constraints.

Table 3.3: List of legal publications reviewed to compile land use allocation constraints.

#	Name of Publication	Year Published
1	Environment Management Act	1996
2	Forestry Act	1997
3	Land Act	2016
4	Physical Planning Act	2016
5	Physical Planning and Development Management Guidebook	2011
6	Public Roads Act	1989
7	Water Resources Act	2013

3.4.2.4 Land Use or Cover Re-patterning of the Lilongwe River Catchment

3.4.2.4.1 Introduction to the Dyna-CLUE model

Development of alternative land use patterning for the catchment required the use of a land use model to facilitate quick conversion of land use types on the current land use map. The Dyna-CLUE model was used for this purpose. This is a geographical land use model that combines the top-down approach to allocation of land use change in a study area with a bottom-up determination of conversions for specific land use transitions (Verburg & Overmars 2009). The model is open-source and has been applied in many different regions across the world and hence was selected for this study (Verburg & Overmars 2009; Lee *et al.* 2011; Le Roux & Augustijn 2017).

3.4.2.4.2 Model Setup

To run, the Dyna-CLUE model requires an initial land cover map, and the area demands of each land use/cover class the user wishes to convert. The initial land cover map entered into the model was the 2019 map produced in Objective 1. Calculation of area demands was based on the effect that each land use/cover class has on streamflow, and the direction of change in the current flow regime that is required to achieve the predefined ideal streamflow regime.

3.4.2.4.3 Model Land Use Change Constraints

The Dyna-CLUE model offers an option to specify areas or situations in which land use types present in an area cannot be converted to another land use type, or under which strict conditions a change is allowed. This option was activated for this study to ensure land use plans generated were steeped in reality and could be used to inform actual potential land development policies in the study area. Use of the option required generation of area restriction files which are raster maps that precisely define areas of land that can or cannot be used for land use conversion. The compiled list of constraints explained in Section 3.4.2.3 was used for the creation of the aforementioned raster maps and used to configure the Dyna-CLUE model. One example of a constraint used was a law that prohibits developments over steeply sloped land. Such areas in the catchment were thus demarcated as restricted areas where land use conversions could not occur.

One other constraint required the definition of the Lilongwe River's 100-year flood buffer zone. This was created using a flood modelling software known as the Hydrologic Engineering Center's River Analysis System (HEC-RAS). This is an integrated software system that models the hydraulics of water flow through different types of water channels (United Stated Army Corps of Engineers 2016). The software allows calculation of one-dimensional steady flow as well as one and two-dimensional unsteady flow which are ideal for floodplain mapping (USACE 2016). It was selected for this analysis because it is open source and has been widely used successfully in catchments with varying hydrologic conditions all across the globe (Yan, Di Baldassarre & Solomatine 2013; Schulz *et al*. 2015; Khattak *et al*. 2016; Khalfallah & Saidi 2018). To execute, the software requires terrain, river bed morphology, and peak flow data which was entered into the model and a 1D steady flow analysis was performed to produce a 100-year flood map of the river. This map was then merged with that of the other restricted areas in the catchment and later used as input for the Dyna-CLUE model.

3.4.2.4.4 Model Land Use Conversion Suitability

The Dyna-CLUE model also offers an option to include suitability layers, which are files that help the model determine the most suitable area for a land cover change to occur. For example, settlements are often situated close to roads or footpaths, therefore cropland or forested areas close to a road network are more likely to convert to settlements than those that are not. Slope, DEM, distance to road, and distance to river maps were used as suitability layers and entered into the model.

For technical reasons, the Dyna-CLUE model is not able to process very high-resolution raster data. As a result, the resolution of all input data used to run the model was resampled to 90x90 meters in cell size using the Resample tool in ArcGIS. Consequently, land use restrictions that would likely affect an area of less than 8100 m^2 at any given point on the land cover map were not included in the list. One example of such a restriction is that 30 meters of road reserve is required for primary roads. Such fine margins cannot be accurately captured by a 90 m resolution raster. Restrictions pertaining to changes in use within the same land use/cover class, such as from industrial to residential land use, were also disregarded.

A land use conversion matrix was created based on the land use types identified in the study area in Objective 1 and the land use change constraints. This matrix defines which conversions are possible for each land use type. By configuring the model to change the hectarage of a particular land use type, the model continuously converted other land use types in the area based on the conversion matrix until the specified hectarage of each land use type was satisfied (Verburg & Overmars 2009). Using this technique iteratively, a total of six re-patterned land use scenarios were created. Each scenario was created based on a potential development driver that may occur naturally or can be promoted by land use planners, and focused on enhancing a particular component of the Lilongwe hydrological cycle towards yielding the ideal streamflow regime. For instance, one land use scenario focused on reducing forest cover which according to several studies decreases runoff (Palamuleni 2009; Geremew 2013; Wangpimool *et al.* 2013; Welde & Gebremariam 2017). Wetland/Grassland and Settlement/bare land classes were assumed to be equally split in proportions of the combined classes to facilitate the creation of some scenarios focused on grassland and bare land.

3.5 Effect of Different Land Use Patterns on the Lilongwe River Flow Regime

3.5.1 Data Collection

Data required to achieve this objective was already collected in objectives 1 and 2. This included the same input data used to run and calibrate the SWAT model in Objective 1, and the practical land use maps produced in Objective 2.

3.5.2 Data Processing and Analysis

3.5.2.1 Effect of Different Land Use Patterns on Flow

Each land use pattern determined for the study area in Objective 2 was used as input to run the calibrated SWAT model from 2020 to 2049. Descriptive statistics such as mean and standard deviation were used to compare differences between the modelled streamflow output from each land use pattern and the current streamflow regime determined in Objective 1. Flow outputs were compared between the dry season (i.e. from July to October), and wet season (i.e. from December to March), as well as annually in light of the well-known seasonal variations of streamflow (Palamuleni 2009; Geremew 2013) against the ideal streamflow regime.

3.5.2.2 Land Use Scenarios Yielding an Ideal Streamflow Regime

Flow duration analysis was performed from the streamflow output produced by each proposed land use scenario to determine whether any scenario could yield the ideal streamflow regime. Any streamflow regime was considered ideal if the probability of exceedance of the lower and upper flow limits determined in Objective 2 were greater than or equal to 99% and 1% respectively. All comparisons and statistical analysis in this objective were done using Microsoft Excel 2016.

CHAPTER FOUR: RESULTS

4.1 Projected Lilongwe River Flow Regime Based on Current Land Cover Pattern in the Catchment

4.1.1 Current Land Cover

Based on the classification of the 2019 satellite images the current pattern of land cover in the Lilongwe River Catchment is presented in Figure 4.1. Table 4.1 further presents the proportions of area covered by each of the 5 land cover classes identified in the catchment based on the same. Results show that a vast majority of land in the study area is dominated by cropland amounting to 830.83 km^2 or 45.83 % of the total area, seconded by trees or forested land at 590.72 km^2 or 32.59 %. The majority of this forested land exists within the protected confines of Dzalanyama forest reserve which is visible as the large block of forest in the south western part of the map in Figure 4.1.

Wetland and grasslands criss-cross the entire Lilongwe River Catchment typically following the tributaries and main channel of the Lilongwe River. These areas were often observed to be used for cultivation by residents and featured water-intensive crops such as sugarcane, bananas, and various vegetables. The crops were grown on the banks of the streams and rivers and sometimes even on the river bed itself. Water bodies cover the least amount of area in the catchment, at only 0.2 % with the most significant portion being the inundation area of Kamuzu Dam 1 and 2 in the centre of the study area.

Settlements are dotted all around the study area typically situated on gentle slopes or along mostly unpaved roads criss-crossing the catchment. The highest concentration of settlements is found in the north eastern part of the study area which features Likuni, and part of Lilongwe City. The unpaved roads constituted a large portion of land classified as bare land which was later combined with the Settlement land class. Bare rock which was classified as bare land was common atop hills or mountains in the Dzalanyama mountain range and at Malingunde town located near the centre of the map.

Based on the error matrix presented in Table 4.2, accuracy assessment of the 2019 land cover map in Figure 4.1 yielded satisfactory results, achieving an overall accuracy of 91.5 %, and a Kappa coefficient of 87.9 %. User and producer accuracies were also satisfactory with reasonably few errors of commission and omission as shown in Table 4.2. The most omission errors occurred in the Settlement/Bare land class, which was sometimes misclassified as cropland. In contrast, most errors of commission were found to occur in the cropland class which erroneously included some wetland/grassland and settlement/bare land class pixels.

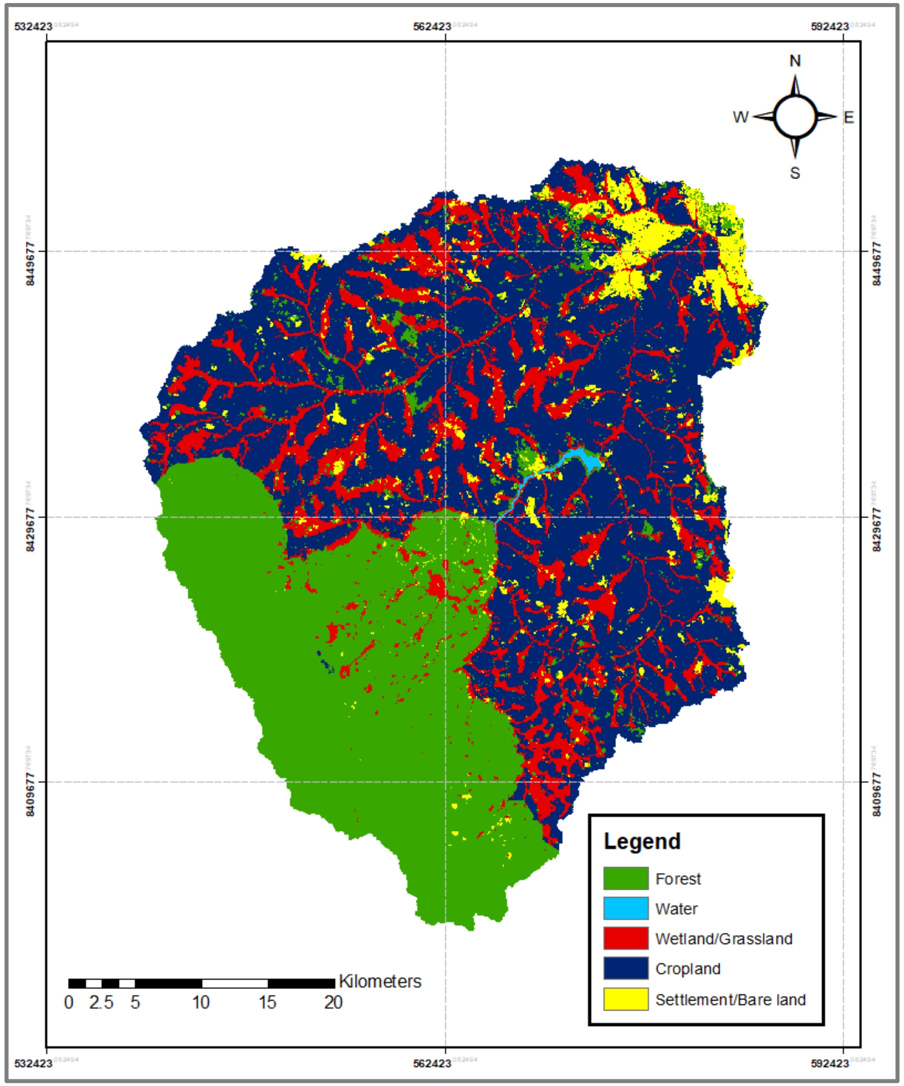

Figure 4.1: 2019 land cover map of the Lilongwe River basin.

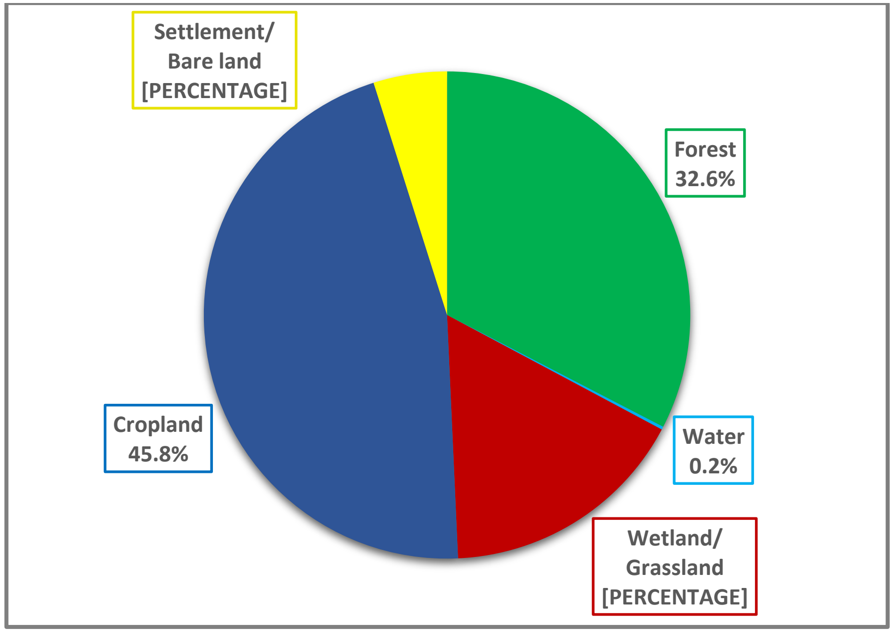

Figure 4.2: 2019 land cover proportions in the Lilongwe River basin.

Table 4.1: 2019 land cover class areas in the Lilongwe River basin.

Land Cover Class	Area (km^2)	Area (%)
Forest	590.72	32.59
Water	3.61	0.20
Wetland/Grassland	298.93	16.49
Cropland	830.83	45.83
Settlement/Bare land	88.56	4.89

Total	**1812.65**	**100**

Table 4.2: Accuracy assessment error matrix for 2019 land cover map.

	Reference Data							
Land Cover Class	Forest	Water	Wetland/ Grassland	Cropland	Settlement/ Bare land	**Total**	**User's Accuracy (%)**	**Errors of Omission (%)**
Forest	59	0	0	0	0	59	**100.0**	**0.0**
Water	0	10	0	0	0	10	**100.0**	**0.0**
Wetland/Grassland	3	0	25	7	0	35	**71.4**	**28.6**
Cropland	0	0	1	77	1	79	**97.5**	**2.5**
Settlement/ Bare land	1	0	0	4	12	17	**70.6**	**29.4**
Total	63	10	26	88	13	200		
Producer's Accuracy (%)	**93.7**	**100.0**	**96.2**	**87.5**	**92.3**		**Overall Accuracy = 91.5%**	
Errors of Commission (%)	**6.3**	**0.0**	**3.8**	**12.5**	**7.7**			

Classified Data

4.1.2 Climate Projections

Precipitation projections from the RCMs were shown to vary quite widely depending on the model. Whilst some models predicted lower average precipitation than in the past 30 years (1990-2019) (e.g. CLMcom-CCLM4-8-17), others predicted much higher amounts (e.g. SMHI-RCA4) as shown in Figure 4.3. This finding is also evident from the trend analysis results given in Table 4.4 which show significant increasing (CCma-CanRCM4 and SMHI-RCA4) or decreasing (CLMcom-CCLM4-8-17) trends (at 95 % confidence interval) in annual precipitation from all but one RCM scenario (MPI-CSC-REMO2009). The Sen's Slope given in the table further reveals that the rate of change in precipitation from 1990 to 2049 would be 6.3 mm, -6.4 mm, and 17.9 mm per year for the CCma-CanRCM4, CLMcom-CCLM4-8-17, and SMHI-RCA4 model scenarios respectively. All RCMs used in this study projected the likely occurrence of extreme rainfall events far exceeding the most extreme that occurred over the last 30 years (see Table 4.3).

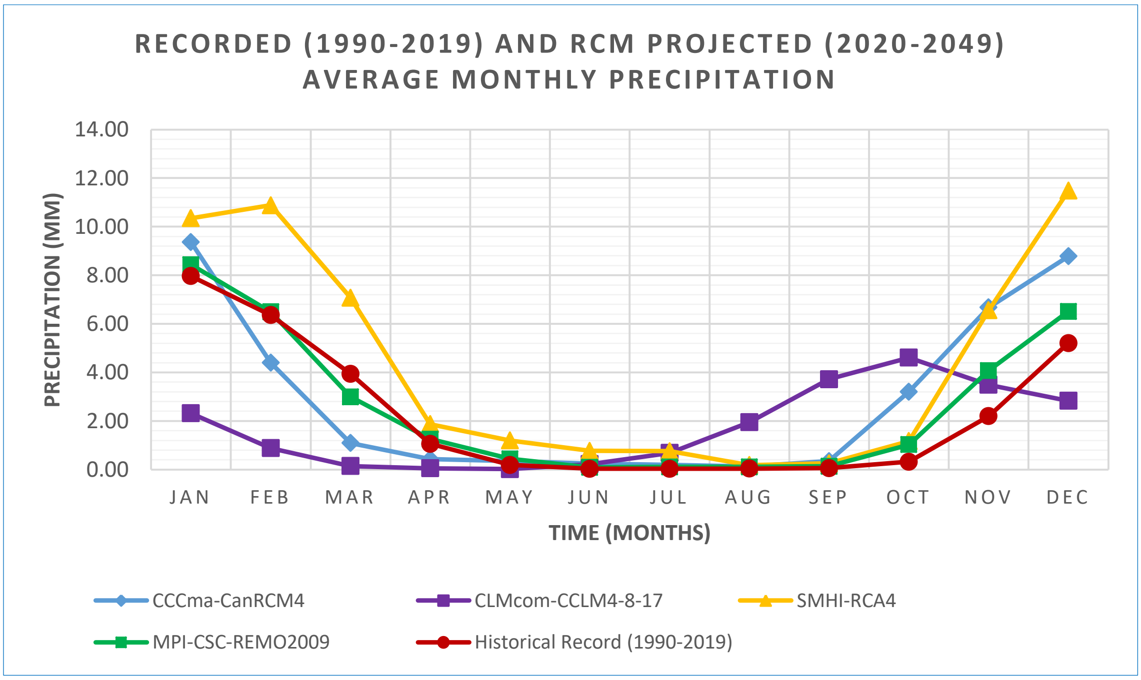

Figure 4.3: Average monthly precipitation projected by RCMs (2020-2049) and recorded at Chitedze Meteorological Station (1990-2019).

Table 4.3: Comparison of annual precipitation data projected by RCMs (2020-2049) and recorded at Chitedze Meteorological Station (1990-2019).

Data Source	Annual Precipitation (mm)		
	Population Mean	Record Max	Standard Deviation
Historical Record (1990-2019)	2.235	122.900	7.750
CCCma-CanRCM4	2.927	166.816	7.281
CLMcom-CCLM4-8-17	1.745	249.706	7.256
SMHI-RCA4	4.372	141.394	8.763
MPI-CSC-REMO2009	2.621	138.953	8.116

Analysis of the RCM temperature projections revealed that 2 of the 4 model scenarios predict higher maximum temperatures in Lilongwe and an increasing trend in maximum temperatures over the next 30 years (see Table 4.4). However, it was apparent from the analyses that the CLMcom-CCLM4-8-17 model does not follow the expected seasonal pattern of rainfall or temperature characteristic of the Lilongwe climate. For instance, unusually high temperature and rainfall amounts were found common in the model's cold dry season output as depicted in Figure 4.3 and Figure 4.4. This model's data was thus deemed erroneous and consequently excluded from further analyses.

Trend analysis revealed mixed results for the minimum temperature projections as well, with 2 out of the 3 valid RCM scenarios showing no significant trends, However, both the SMHI-RCA4 and the RCM ensemble show a significant increase occurring (see Table 4.4). Additionally, looking at the projected data between 2020 to 2049 independently, the RCM ensemble scenario projected minimum and maximum temperatures to increase by an average of 0.94 ℃ and 2.46 ℃, respectively.

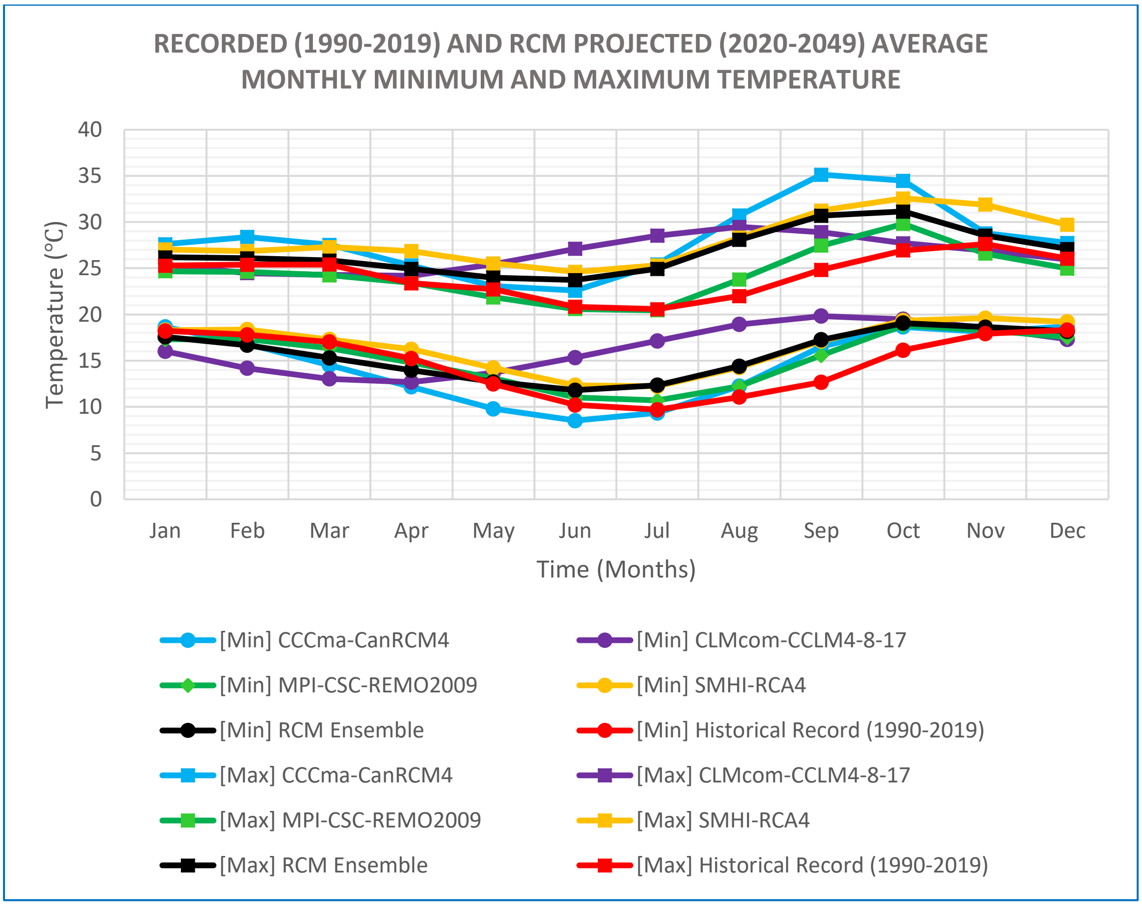

Figure 4.4: Average monthly maximum and minimum temperatures projected by RCMs and recorded at Chitedze Meteorological Station.

Table 4.4: Trend analysis results of annual climatic variables showing Mann-Kendall statistic (S), z-statistic (z), and Sen's Slope (β).

Data Source	Precipitation (mm)				Minimum Temperature (°C)				Maximum Temperature (°C)			
	S	**z**	**β**	**Result**	**S**	**z**	**β**	**Result**	**S**	**z**	**β**	**Result**
CCCma-CanRCM4	610	3.884	6.275	Sig.	117	0.76	1.997	Not Sig.	553	3.61	10.789	Sig.
CLMcom-CCLM4-8-17	-540	-3.438	-6.424	Sig.	113	0.73	17.582	Not Sig.	-276	-1.754	-3.385	Not Sig.
SMHI-RCA4	377	2.46	17.927	Sig.	411	2.68	7.342	Sig.	-347	-2.26	-20.608	Sig.
MPI-CSC-REMO2009	276	1.754	2.460	Not Sig.	213	1.39	19.118	Not Sig.	483	3.15	9.799	Sig.
RCM Ensemble	-	-	-	-	331	2.16	8.606	Sig.	-22	-0.13	-0.198	Not Sig.

Note: at 95% confidence interval, z-statistic critical value is 1.96. Sig. = Significant, Not Sig. = Not Significant.

4.1.3 Flow Regime Projections

Calibration and validation of the SWAT model yielded satisfactory results showing an acceptable level of correspondence between daily simulated streamflow and the daily observed streamflow data. The calibration process yielded an NSE of 0.65 and an R^2 of 0.64, whilst validation yielded an NSE of 0.62 and an R^2 of 0.62 as well. These values meet the accepted minimum value limits of 0.5 for the NSE and 0.6 for R^2 mentioned previously. This confirmed that hydrological processes involved in streamflow generation in the catchment were being adequately replicated by the model (Santhi *et al*. 2001; Moriasi *et al*. 2007). Figure 4.5 and Figure 4.6 below present the flow hydrographs produced from the calibration and validation processes respectively and depict simulated flow along with observed flow data. The graphs also display the 95 percent prediction uncertainty (95PPU) band, which is a distribution between the 2.5th and 97.5th percentiles of parameter prediction uncertainty.

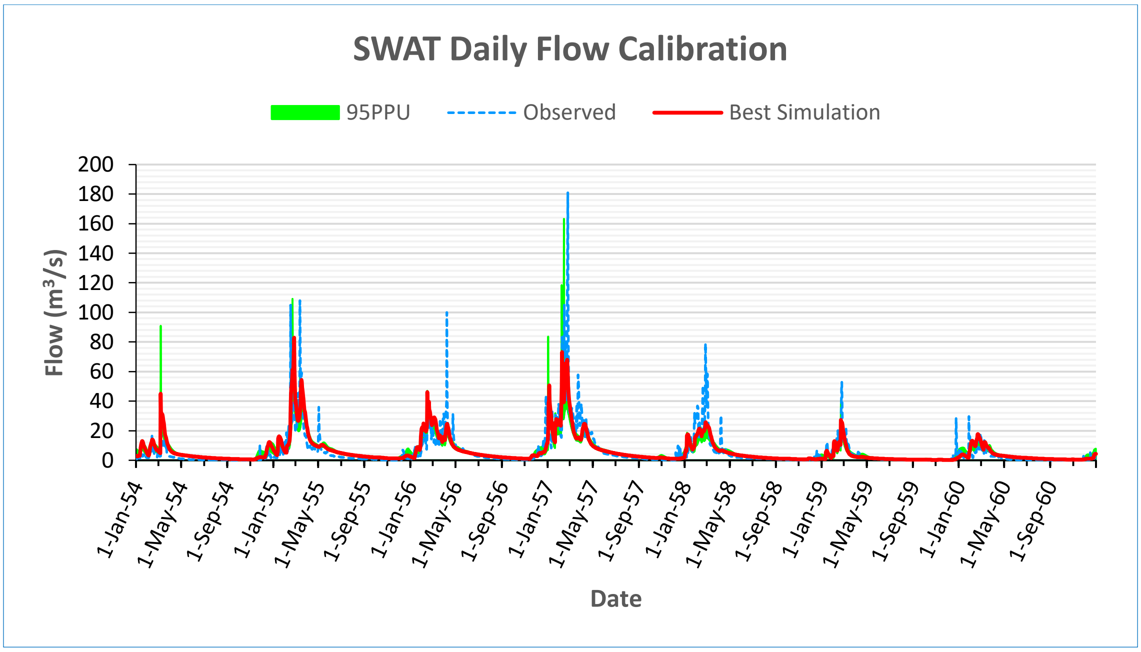

Figure 4.5: Calibration results for SWAT simulation of daily flow in Lilongwe River.

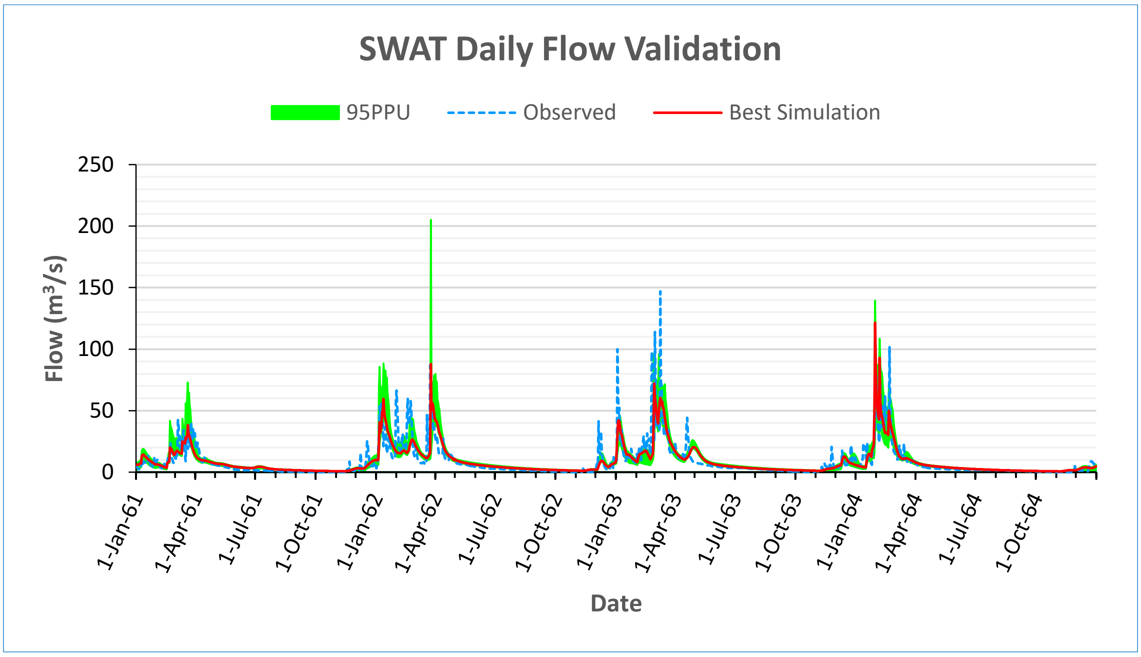

Figure 4.6: Validation results for SWAT simulation of daily flow in Lilongwe River.

The calibrated SWAT model was executed with different RCM climate data to produce streamflow output based on each RCM scenario. Results of this analysis revealed that all RCM scenarios will result in higher average flow amounts than in previous recorded years which recorded an overall annual average streamflow of 10.1 m^3/s. The highest annual average flow increase was a product of the SMHI-RCM4 model which registered an average annual flow of 42.5 m^3/s, a four-fold increase from the recorded data. In contrast, the average monthly flow output from the MPI-CSC-REMO2009 scenario showed striking similarity to that of the historical record, with an increase of only 0.6 m^3/s over the historical record. Figure 4.7 presents the average monthly flow for both the recorded and projected RCM scenarios.

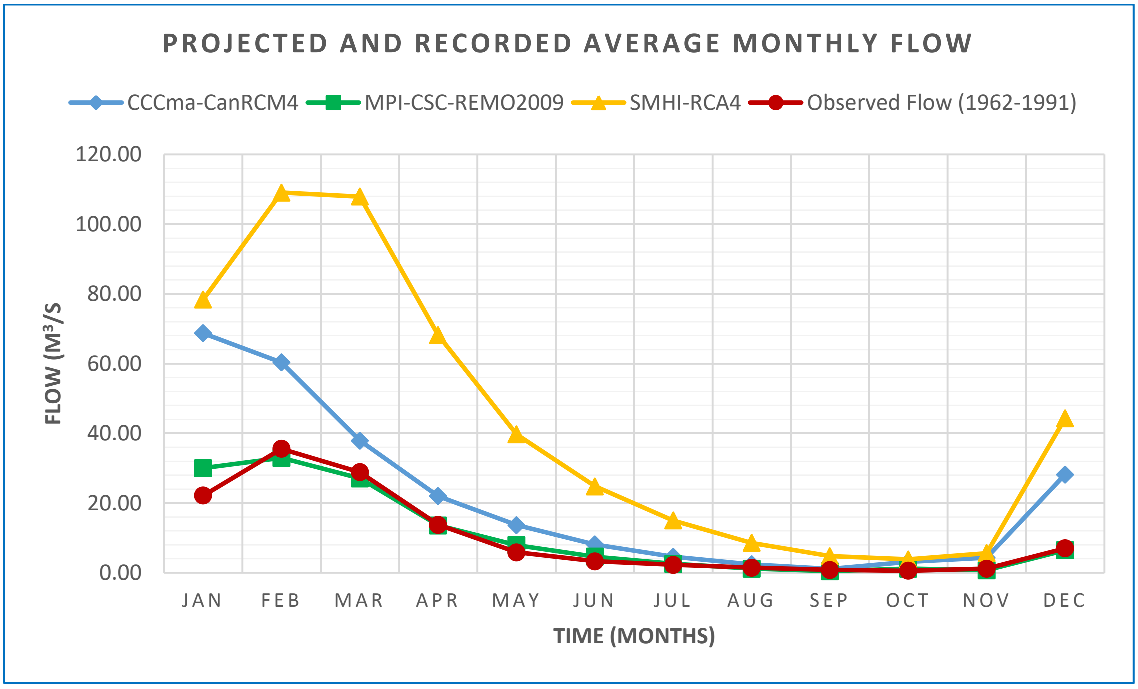

Figure 4.7: Average monthly hydrograph of recorded and projected flows in Lilongwe River.

Results also showed a potential increase in the magnitude of flood events. The CCCma-CanRCM4 scenario for instance registered a maximum flow amount of 1211 m^3/s. Using the flood frequency curve derived from observed river data shown in Figure 4.8, a flow of this magnitude can be described as a 1100-year flood. The MPI-CSC-REMO2009 and SMHI-RCM4 scenarios also projected very high flood flows of 1115 m^3/s and 988.3 m^3/s respectively, which are both greater than the observed record high of 958.3 m^3/s.

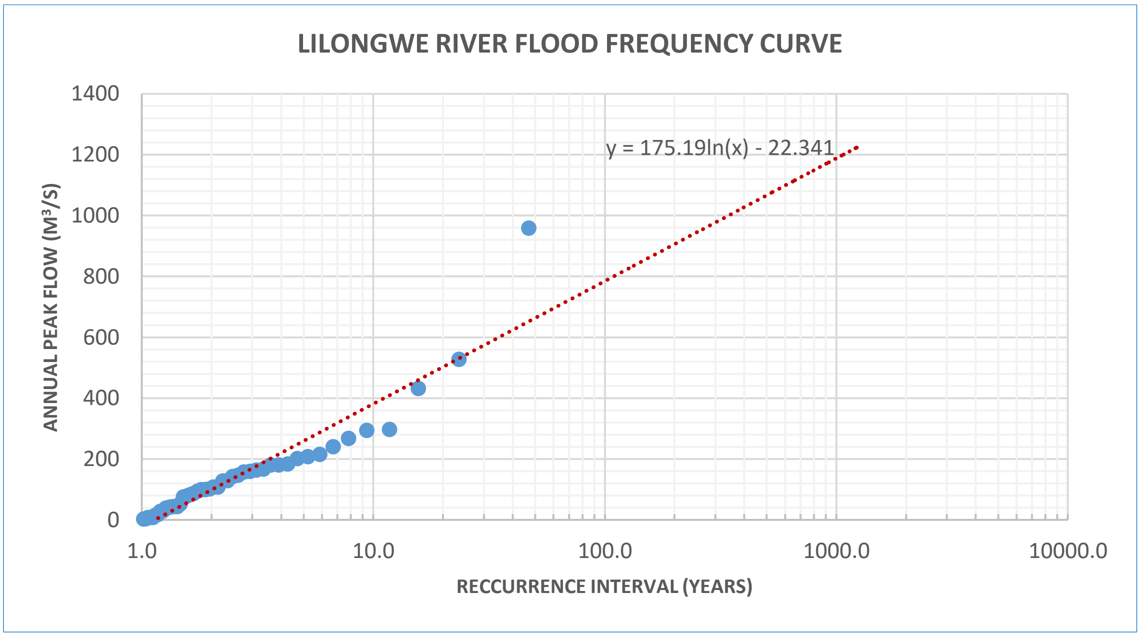

Figure 4.8: Lilongwe River flood frequency curve.

Table 4.5 presents a comparison of the changes that are projected to occur in the Lilongwe River's flow regime as a result of each RCM scenario. All but one RCM scenarios (MPI-CSC-REMO2009) project substantial increases in average streamflow during the dry season. Results also show minimum flows during the dry season are projected to fall below 1.5 m^3/s even in the SMHI-RCM4 high flow scenario.

Table 4.5: Comparison of average annual historical (1962-1991) and RCM projected (2020-2049) flows in the Lilongwe River.

Data Source	Average Wet Season Flow (Dec, Jan, Feb, Mar)			Average Dry Season Flow (Jul, Aug, Sep, Oct)		
	Flow (m^3/s)	Change (m^3/s)	% Change	Flow (m^3/s)	Change (m^3/s)	% Change
Observed Flow (1962-1991)	23.39	-	-	1.28	-	-
CCCma-CanRCM4	48.78	+25.38	+109%	2.81	+1.53	+120%
MPI-CSC-REMO2009	24.12	+0.73	+3%	1.33	+0.05	+4%
SMHI-RCA4	84.92	+61.52	+263%	8.04	+6.76	+528%

Figure 4.9 presents the Flow Duration Curves (FDCs) for the Lilongwe River based on observed flow records, as well as on the RCM-driven SWAT outputs. These graphs chart the probability of flow in the river exceeding a particular threshold at any given time which often becomes the basis for water use planning. All but one RCM scenario (MPI-CSC-REMO2009) projects higher flow amounts at almost all exceedance probabilities. In fact, the FDCs show that the likelihood of the MPI-CSC-REMO2009 scenario flow output exceeding the observed record is only 22.95%, at very high discharge levels. The curves further show that despite projecting high magnitude floods, all RCM driven scenarios predict floods will continue to be a rare event with the 100-year flood threshold being exceeded no more than 0.06% of the time.

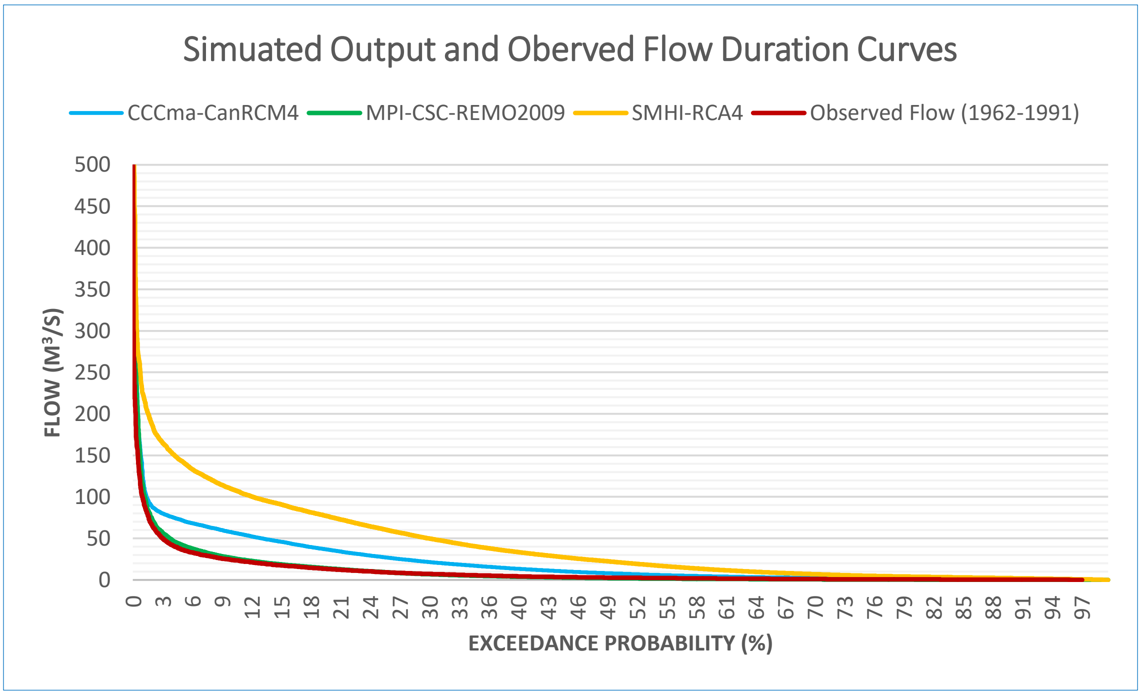

Figure 4.9: Observed (1962-1991) and RCM-driven simulated (2020-2049) flow duration curves (FDCs) for Lilongwe River.

Figure 4.10 summarizes the most important takeaways from Figure 4.9 with simplified FDCs from the 1st to 99th percentile exceedance probabilities. One finding especially worthy of note is that all projected future scenarios forecast streamflow will remain below 2.15 m^3/s at least 10% of the time which is the total current water demand from the river. Figure 4.10 charts this current demand and further shows that all but one RCM scenario (SMHI-RCM4) would result in a water deficit at least 25% of the time. The MPI-CSC-REMO2009 scenario also projects water shortage to occur over 50% of the time which is especially concerning considering this scenario most resembles the historical record.

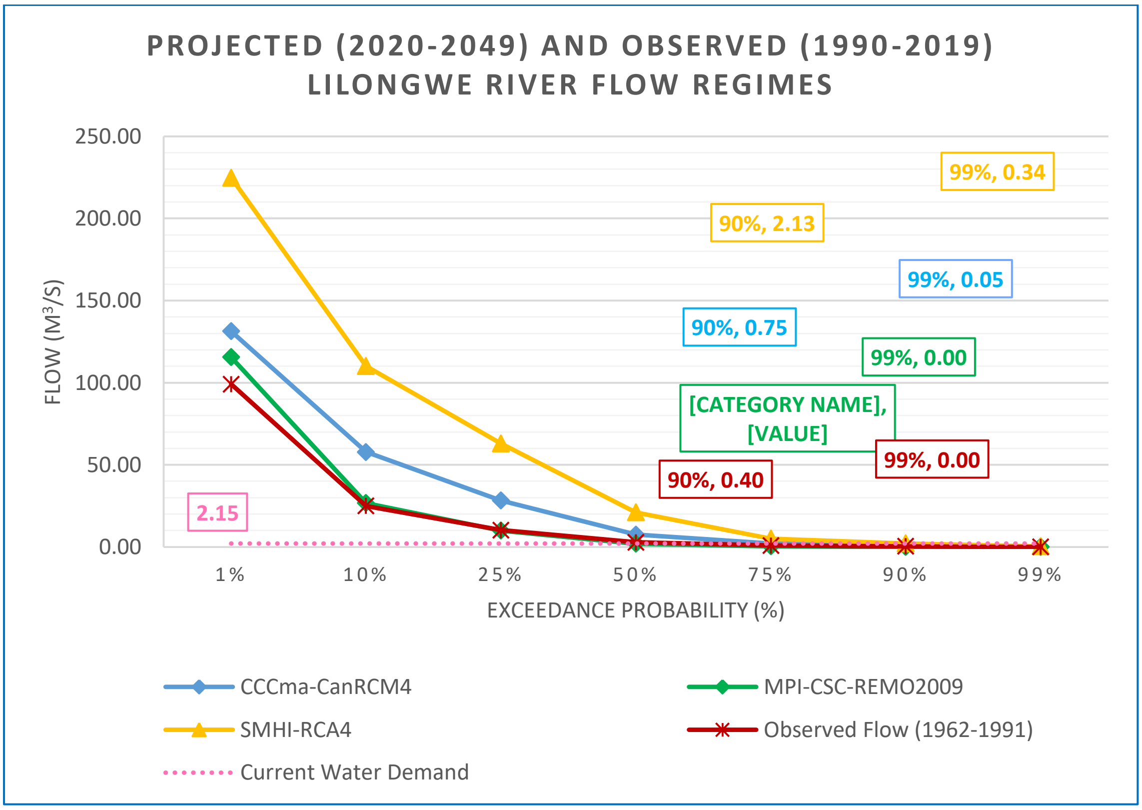

Figure 4.10: Simplified flow duration curves for Lilongwe River based on observed (1962-2019) and RCM-driven simulated (2020-2049) flow.

4.2 Practical Land Use Scenarios for the Lilongwe River Catchment Based on Ideal Streamflow Regime Requirements

4.2.1 Ideal Streamflow Regime

An ideal streamflow regime was defined as one that likely varies between a minimum flood level, defined here as the 100-year flood discharge, and the 2049 projected water demand from licensed abstractors. Figure 4.8 shows the 100-year flood discharge in the Lilongwe River is 784.45 m^3/s. Data collected from NWRA and LWB show LWB is by far the most consumptive abstractor of water from the Lilongwe River, currently withdrawing about 1.45 m^3/s (125,000 m^3/day) of water which accounts for about 99.71% of total licensed abstractions. An exponential trend line extending 10 years from current official LWB projections (Figure 4.11) projects water demand from LWB to total about 5 m^3/s (431,718 m^3/day) by 2049. Abstraction from other licensees total just 0.0036 m^3/s (370 m^3/day) which was considered very negligible and thus disregarded since near-future changes to this demand are likely to be negligible as well (LWB 2020).

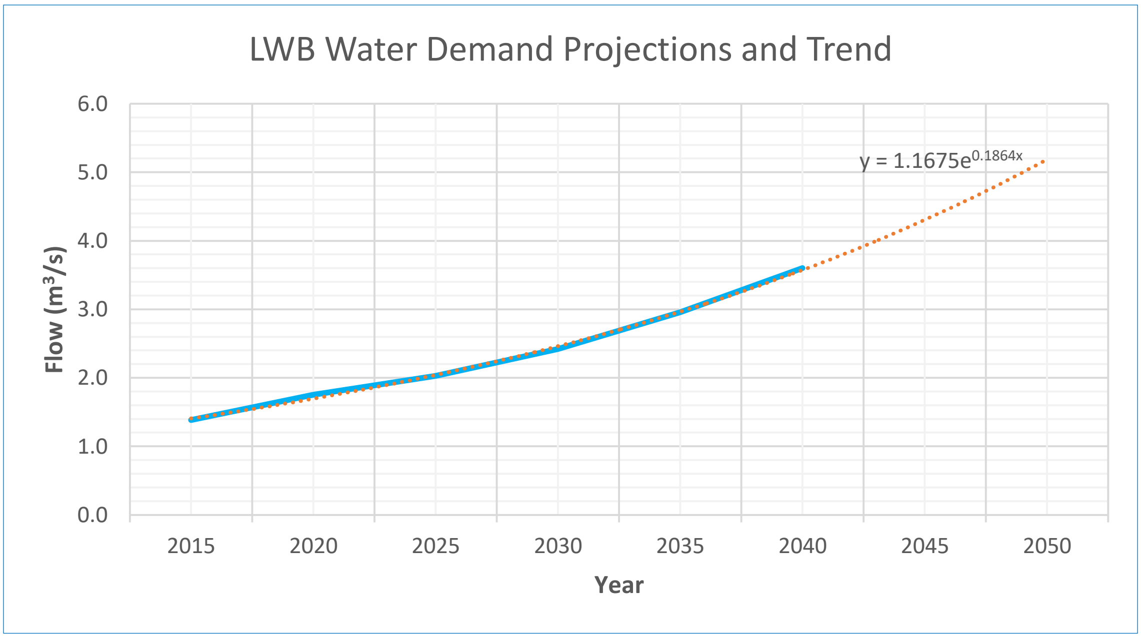

Figure 4.11: Current LWB water demand projections and extrapolated trend line to 2049.

Table **4.6** presents the LWB water demand projections from the utility summed up with the abstractions from other licensees and the environmental flow (0.4 m^3/s). An ideal streamflow regime was therefore defined as one whose probability of exceeding 784.45 m^3/s and 5 m^3/s was greater than or equal to 99 % and 1% respectively.

Table 4.6: Projected total water demand and environmental flows for Lilongwe River.

Year	Demand (m^3/day)	Demand (m^3/s)	Demand + Environmental Flow (m^3/s)
2015	119,718	1.39	1.79
2020	151,308	1.75	2.15
2025	175,308	2.03	2.43
2030	209,308	2.42	2.82
2035	255,308	2.95	3.36
2040	311,308	3.60	4.00
2045	372,218	4.31	4.71
2049	431,718	5.00	5.00

4.2.2 Relative Effect of Land Cover Classes on Projected Flow Regime

The calibrated SWAT model was executed using homogenous land cover maps to compare the effects of each land cover class on streamflow in the catchment. Figure 4.12 and Figure 4.13 present the results of this analysis by comparing the average dry and wet season flow output, respectively, from each simulation based on the land cover class and RCM data used. Similar to the current flow regime, the results show that the SMHI-RCA4 model scenario results in the highest discharge in the Lilongwe River (from 7.5 to 8.5 m^3/s, and 85 to 104 m^3/s in the dry and wet season respectively), whilst the MPI-CSC-REMO2009 produces the lowest (from 1.3 to 2.8 m^3/s, and 18.3 and 44.3 m^3/s).

Results also show that the sensitivity of flow outputs from the different land maps vary mainly based on the RCM data used in both the wet and dry seasons. For example, the results show that the homogenous bare land map produced higher average streamflow in the dry season than any other homogenous land map type created when used along with the CCma-RCM4 and MPI-CSC-REMO2009 model scenarios. However, the same map resulted in the lowest flow output when used with the SMHI-RCA4 model data.

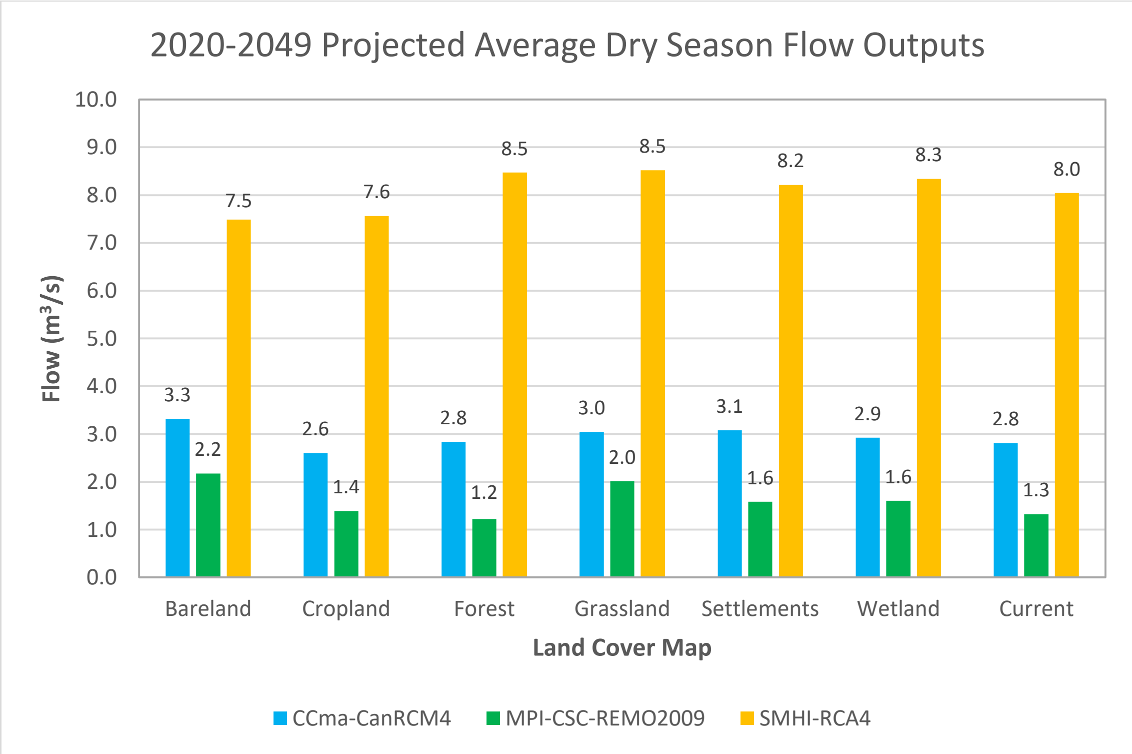

Figure 4.12: Average dry season flow outputs for 2020-2049 period from RCMs and homogenous land cover maps.

Overall, one important takeaway from Figure 4.12 and Figure 4.13 is that the flow resulting from the current land cover map was consistently found to be the third lowest in all RCM scenarios in the dry season, and in 2 out of the 3 RCM scenarios in the wet season. Bare land, grassland, wetland and settlement classes usually resulted in increased flow during the dry season as compared to the current land cover, while only cropland more often resulted in decreased flows in the same season. Results also show that bare land, cropland and grassland produce higher streamflow during the wet season than the current land cover in 2 out of 3 RCM scenarios, while both forest and wetland produce lower streamflow in the same season.

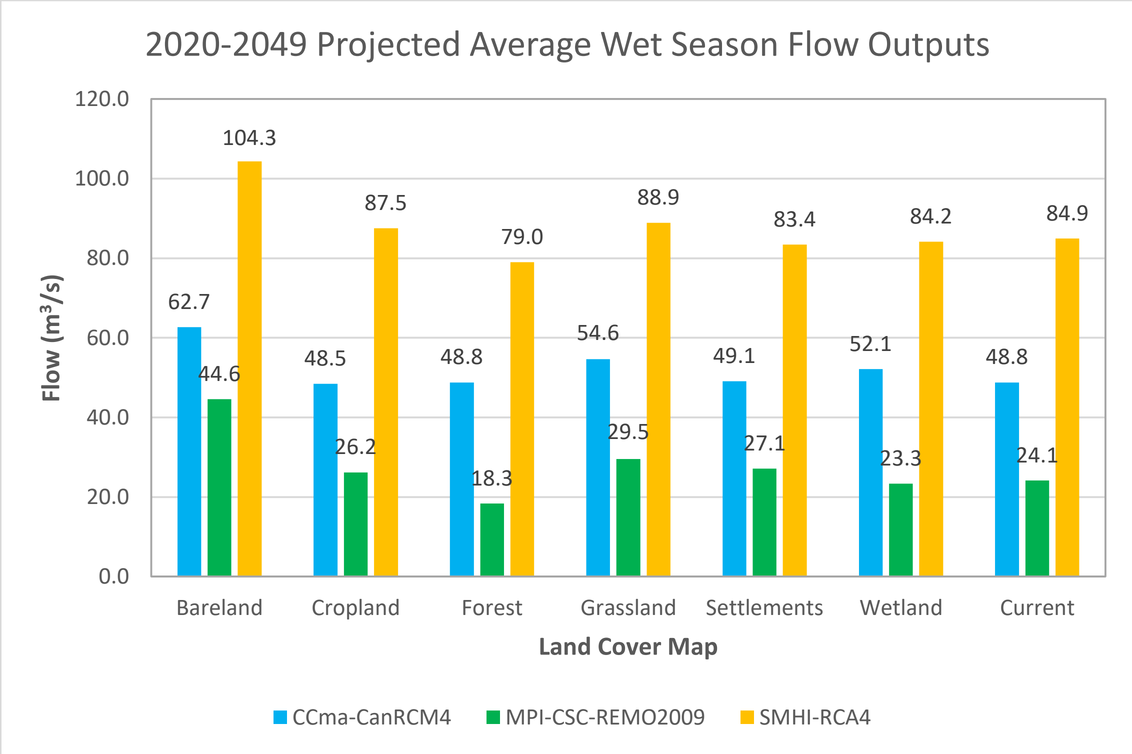

Figure 4.13: Average wet season flow outputs for 2020-2049 period from RCMs and homogenous land cover maps.

It is also worth noting that there were significant differences between flow outputs from the different land cover-RCM scenario combinations in both the dry and wet season (see Table 4.7 and Table 4.8). The maximum negative change in dry season flow output as compared to that of current projections was 8.1 % resulting from the combination of the forest land cover map and the MPI-CSC-REMO2009 climate scenario. The maximum positive change of the same however, was 64 % and was produced by combination of bare land cover and the MPI-CSC-REMO2009 climate scenario. In the wet season, the maximum negative flow change was also registered by the Forest-MPI-CSC-REMO2009 combination at 23.9 %, and maximum positive change was also from the bare land-MPI-CSC-REMO2009 combination.

Table 4.7: Dry season average flow output comparisons.

Statistic	CCma-CanRCM4	MPI-CSC-REMO2009	SMHI-RCA4
Average:	3.0	1.7	8.1
Standard Deviation:	0.2	0.4	0.5
Minimum:	2.6	1.2	7.5
Max Negative Change	-0.2	-0.1	-0.6
Max Negative Change (%)	-7.4	-8.1	-6.9
Maximum:	3.3	2.2	8.5
Max Positive Change	0.5	0.8	0.5
Max Positive Change (%)	18	64	6

Table 4.8: Wet season average flow output comparison.

Statistic	CCma-CanRCM4	MPI-CSC-REMO2009	SMHI-RCA4
Average:	52.6	28.2	87.9
Standard Deviation:	5.5	8.9	8.8
Minimum:	48.5	18.3	79.0
Difference of Min to Current	-0.3	-5.8	-5.9
Difference of Min to Current (%)	-0.6	-23.9	-7.0
Maximum:	62.7	44.6	104.3
Difference of Max to Current	13.9	20.4	19.4
Difference of Max to Current (%)	28	85	23

More details on the underlying causes of the differences in flows explained above are illustrated in Figure 4.14 and Figure 4.15 which present the runoff, evapotranspiration, infiltration, and baseflow from each homogeneous land cover map and climate scenario combination. In all climate scenarios, results show that bare land and settlements are responsible for the highest amounts of runoff from the catchment during the dry season, increasing runoff by up to 5159 % from the current value in the bare land map and

SMHI-RCA4 climate combination. Bare land and cropland maps resulted in the highest runoff in the catchment during the wet season, increasing runoff by up to 161 % from the current amount in the bare land map and MPI-CSC-REMO2009 climate combination. On the contrary, forest land cover was shown to cause the highest decreases in runoff in both the dry and wet seasons by up to -100 % and -48.5 % respectively, both in the forest map and MPI-CSC-REMO2009 climate combination.

Figure 4.14 and Figure 4.15 also show that the highest evapotranspiration losses from the catchment are caused by vegetated land, especially that covered by forests. The homogeneous forest land cover map increased evapotranspiration in both the wet and dry season by up to 99 % and 6 % relative to current projections in the MPI-CSC-REMO2009 and SMHI-RCA4 climate scenarios respectively. In contrast, bare land and cropland maps produced the least amount of evapotranspiration, reducing it by up to -59.3 % in the cropland and MPI-CSC-REMO2009 climate combination.

Concerning infiltration, results show there are minute differences in the effect of each land cover type on infiltration rates, with the highest increase from the current value amounting to only 5 % which was produced by cropland in the CCma-CanRCM4 and SMHI-RCA4 climate scenarios. The differences are more prominent during the wet season with forested land and wetlands showing the greatest propensity to increase infiltration, up to +10 % in the forest map and SMHI-RCA4 climate scenario. In contrast, bare land generally reduced infiltration the most in both the dry and wet season by up to -10.8 % and -28.5 % in the CCma-CanRCM4 and MPI-CSC-REMO2009 climate scenarios respectively. Baseflow also showed minute differences between the land cover types in the dry season with changes amounting to no more than 0.1 m^3/s, but the largest increases from the current projection were produced by forested land at 10 %. All land cover maps produced reduced baseflow during the wet season, however the largest reductions were produced by the bare land map at -38.6 % and -43.8 % in both the dry and wet season respectively and both in the MPI-CSC-REMO2009 climate scenario.

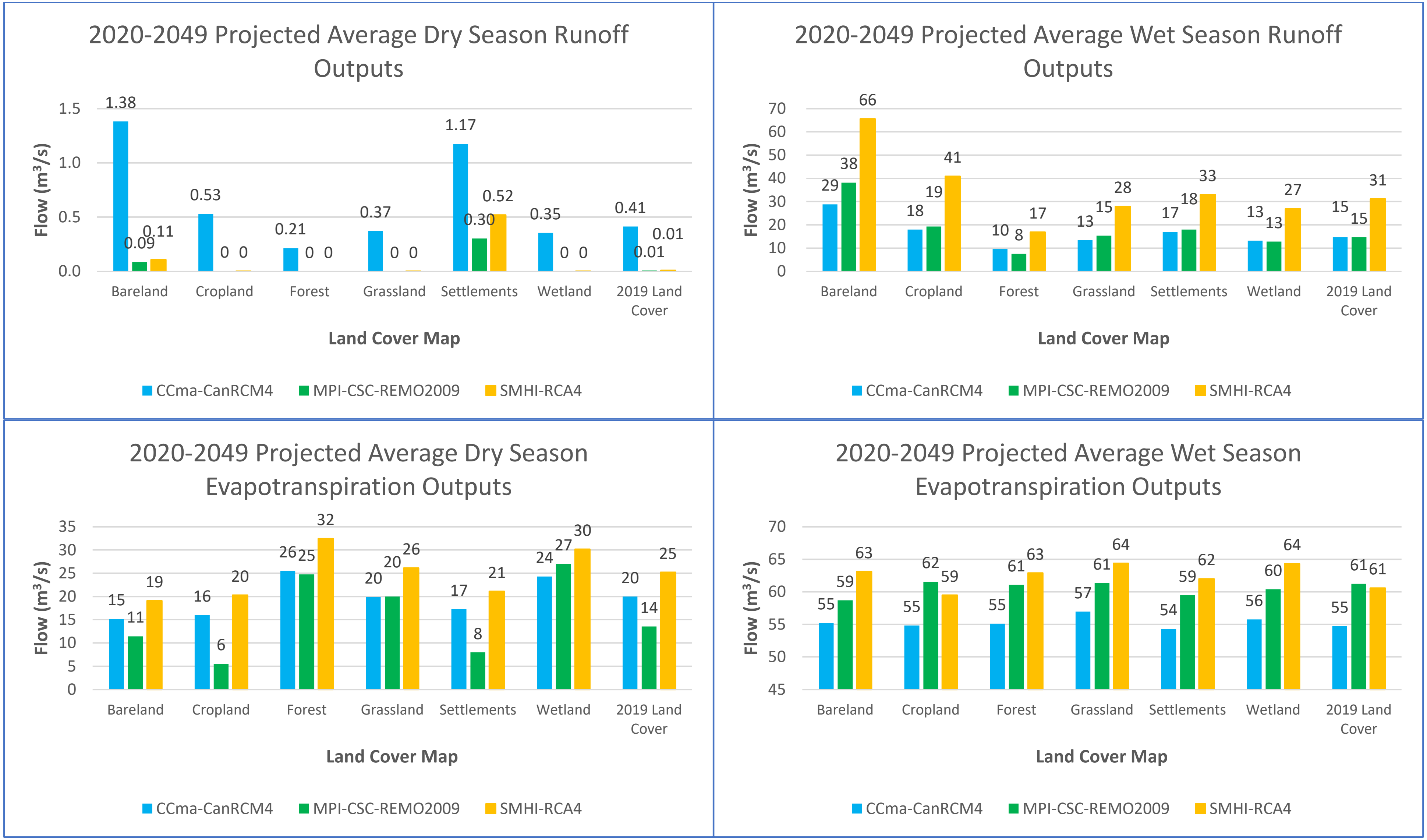

Figure 4.14: Comparison of 2020-2049 projected average dry and wet season runoff and evapotranspiration outputs.

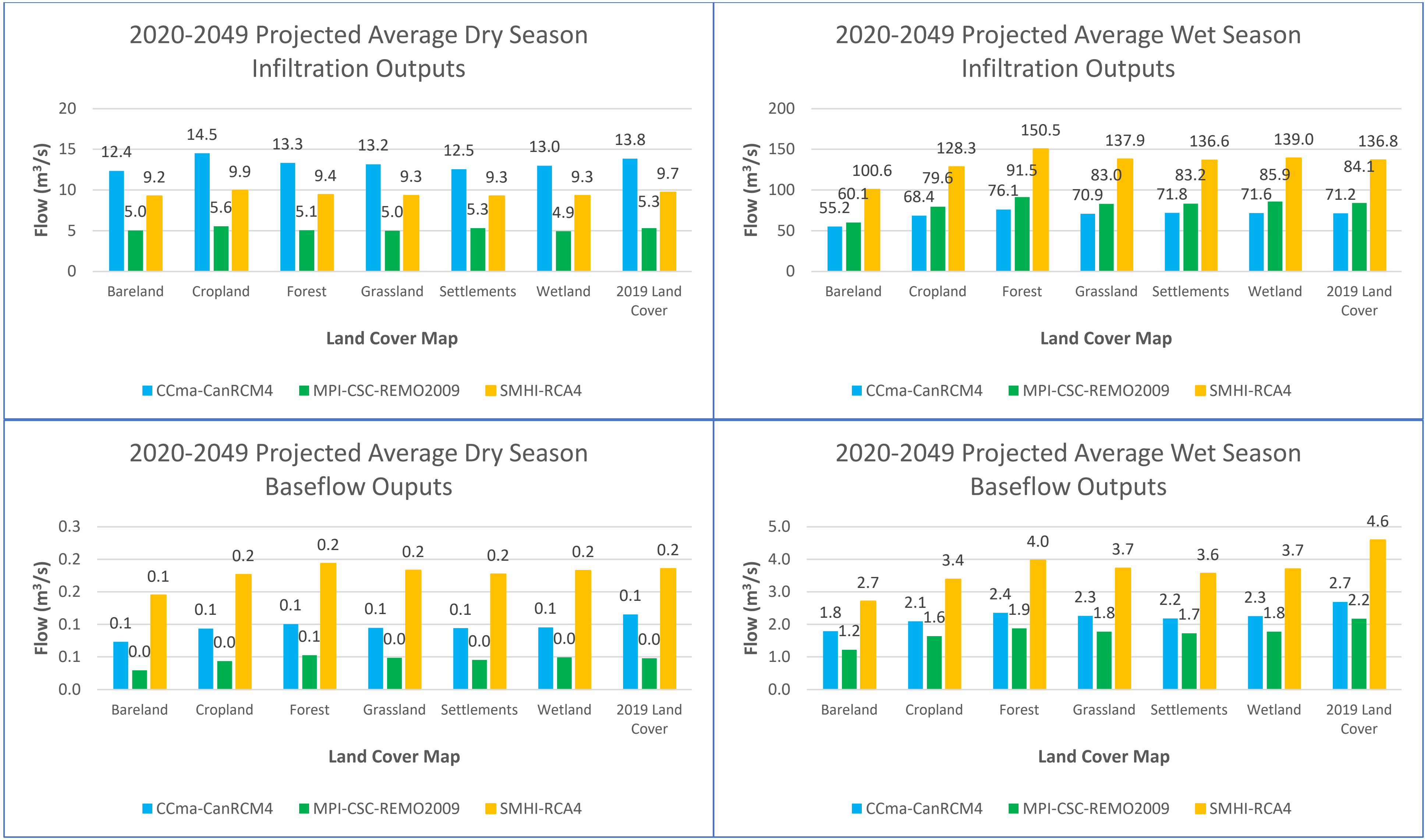

Figure 4.15: Comparison of 2020-2049 projected average dry and wet season infiltration and baseflow outputs.

4.2.3 Legal and Institutional Guidelines for Land Use Allocation in Malawi

Transcripts of the key informant interviews conducted are presented in Appendix 8.2. The informants interviewed explained that land use planning in Malawi is performed by the Department of Physical Planning in conjunction with other relevant government departments. They also explained that land use planning is mainly guided by the National Physical Development Plan (NPDP) (GoM 1987), and that specific allocation of land is usually based on the compatibility of the land for an intended purpose. Areas with rough terrain for example are usually unsuited for building construction or agriculture, hence such areas may be designated for forestry among other uses. Other considerations also include the historical precedent of activities in an area. Lilongwe City for example is known as the administrative capital of Malawi, as such, a large portion of land is dedicated to residential areas which are expected to continue growing at a fast rate as compared to the commercial capital Blantyre for example.

The informants reported that beyond the NPDP, legal restrictions to land use allocation are applied based on existing legislation such as the Physical Planning Act, Environmental Management Act, Water Resources Act, and Physical Planning and Development Management Guidebook. They emphasized that land use plans need to be comprehensive as they also guide the provision of infrastructure and social services in an area. As such, physical planners are not only restricted to environmental laws, but also use legislation such as the Public Roads Act and national standards for social services such as health centres and schools. Detailed layout plans developed are therefore assessed environmentally and socially before being approved by responsible authorities.

A review of all the legislation mentioned above revealed that the Physical Planning and Development Management Guidebook (GoM 2011) contains the most detailed descriptions (i.e. actual specification of dimensions and figures) of restrictions on land allocations. This document was thus used to identify most of the restrictions summarised in Table 4.9 which were used for the creation of area restriction files used in the configuration of the Dyna-CLUE model as described in the table.

Table 4.9: List of land use restrictions used to configure the Dyna-CLUE model.

#	Description of restriction	Dyna-CLUE Configuration/ Consideration
1.	Impervious land coverage must be minimized and should not be higher than 20 % in an aquifers watershed.	Calculation of new land use proportions for the Settlements land class was not allowed to exceed 20% of the total catchment area.
2.	Development within a 100-year floodplain is prohibited.	Conversion of areas within the 100-year flood buffer zone to the Settlement or Cropland class was restricted.
3.	Development on wetlands is prohibited.	Conversion of the wetlands land cover class to the Settlements class was restricted.
4	Development in the upland of wetlands has to be controlled	Conversion of any land cover in the Dzalanyama mountain range to the Settlement class was restricted.
5.	The alteration of steep slopes, ridgelines and hilltops is prohibited.	Conversion of steep sloped areas in the catchment to the Settlement or Cropland class was restricted.
6.	Development in nature sanctuaries has to be controlled.	Land use conversion to Settlement or Cropland classes in all protected areas was restricted.
7.	Development in natural/indigenous forests has to be controlled.	Land use conversion to Settlement or Cropland classes in all protected areas was restricted.
8.	Development in historic, cultural, or archaeological sites has to be controlled.	No significantly large historic, cultural, or archaeological areas were identified in the catchment.

4.2.4 Proposed Land Use Scenarios

Studying the current Lilongwe River regime projections established in Objective 1, it was evident that the biggest problem facing the catchment with regards to streamflow was the low discharge levels that occasionally occurred especially during the dry season. Therefore, to achieve an ideal streamflow regime, all land use scenarios were created with the aim of increasing dry season water flow in the river. Considering the effects of land cover on streamflow explained in Section 2.1.3, the study focused on increasing proportions of land cover types that result in more runoff, namely settlements, grassland, and bare land. The Dyna-CLUE model was successfully configured and executed to produce a total of 6 potential land use scenarios for the Lilongwe River Catchment presented in Figure 4.16 and Figure 4.17 based on these assumptions.

Table 4.10 presents details about each proposed land use scenario, including the potential driver of the land use change, the proportion quantities targeted when modelling, and the final proportions of each land use/cover class. Scenarios A considers a very rapid urbanisation scenario in which urban centres in the catchment grow by 200%. Since the proportion of settlements is relatively small in the catchment, this scenario expands settlement land only to 14.8 %. Scenario B also proposes rapid urbanisation coupled with very rapid expansion of bare land surfaces amounting to 10 % and 9.9 % respectively. Scenarios C proposes the conversion of forested land and cropland to urban settlements (+100 %) and grassland (+50 % the area of wetlands), while Scenario D proposes increases in grassland only. Scenarios E and F consider the conversion of cropland and forest within the Dzalanyama Forest Reserve to bare land and grassland, and the latter scenario also includes an increase in settlements.

Table 4.10: Descriptions of land use scenarios proposed (highlighted cells indicate an increase in area occurred).

SCENARIO	A		B		C		D		E		F	
DRIVER	Rapid Urbanisation		Urbanisation and Deforestation		Pasture Cultivation and Urbanisation		Pasture Cultivation		Dzalanyama Forest Deforestation		Dzalanyama Forest Deforestation and Urbanisation	
MODEL TARGETS	Settlements: +200%		Settlements: +100%, Bare land: +200%		Settlements: +100%, Grassland: +50%		Grasslands: +100%		Grasslands: +100%, Bare land: +100%		Grasslands: +100%, Settlements: +100%, Bare land: +100%	
LAND USE OR COVER CLASS	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**
Forest	574.14	31.7	533.86	29.5	591.92	32.7	534.24	29.5	419.99	23.2	420.21	23.2
Water	3.65	0.2	3.65	0.2	3.65	0.2	3.65	0.2	3.65	0.2	3.65	0.2
Wetland	296.07	16.3	295.42	16.3	296.68	16.4	294.52	16.2	294.52	16.2	294.52	16.2
Cropland	669.89	37.0	620.32	34.2	595.20	32.8	596.49	32.9	623.17	34.4	542.54	29.9
Settlement	268.97	14.8	180.38	10.0	178.72	9.9	89.96	5.0	89.79	5.0	89.79	5.0
Bare land	0.00	0.0	179.12	9.9	0.00	0.0	0.00	0.0	87.77	4.8	179.59	9.9
Grassland	0.00	0.0	0.00	0.0	146.59	8.1	293.91	16.2	293.88	16.2	282.47	15.6

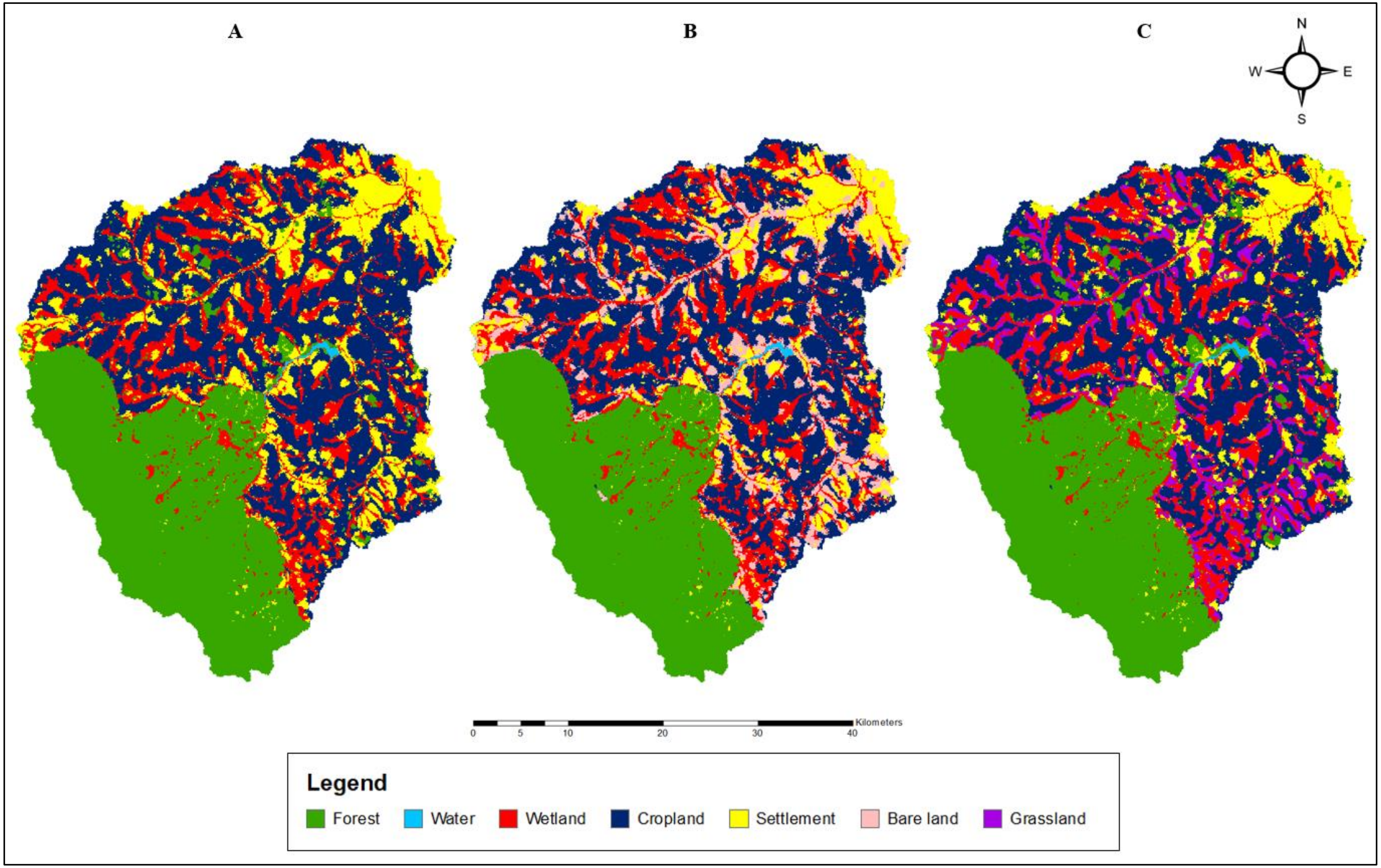

Figure 4.16: Potential land use scenarios **A**, **B**, and **C** proposed for Lilongwe River Catchment.

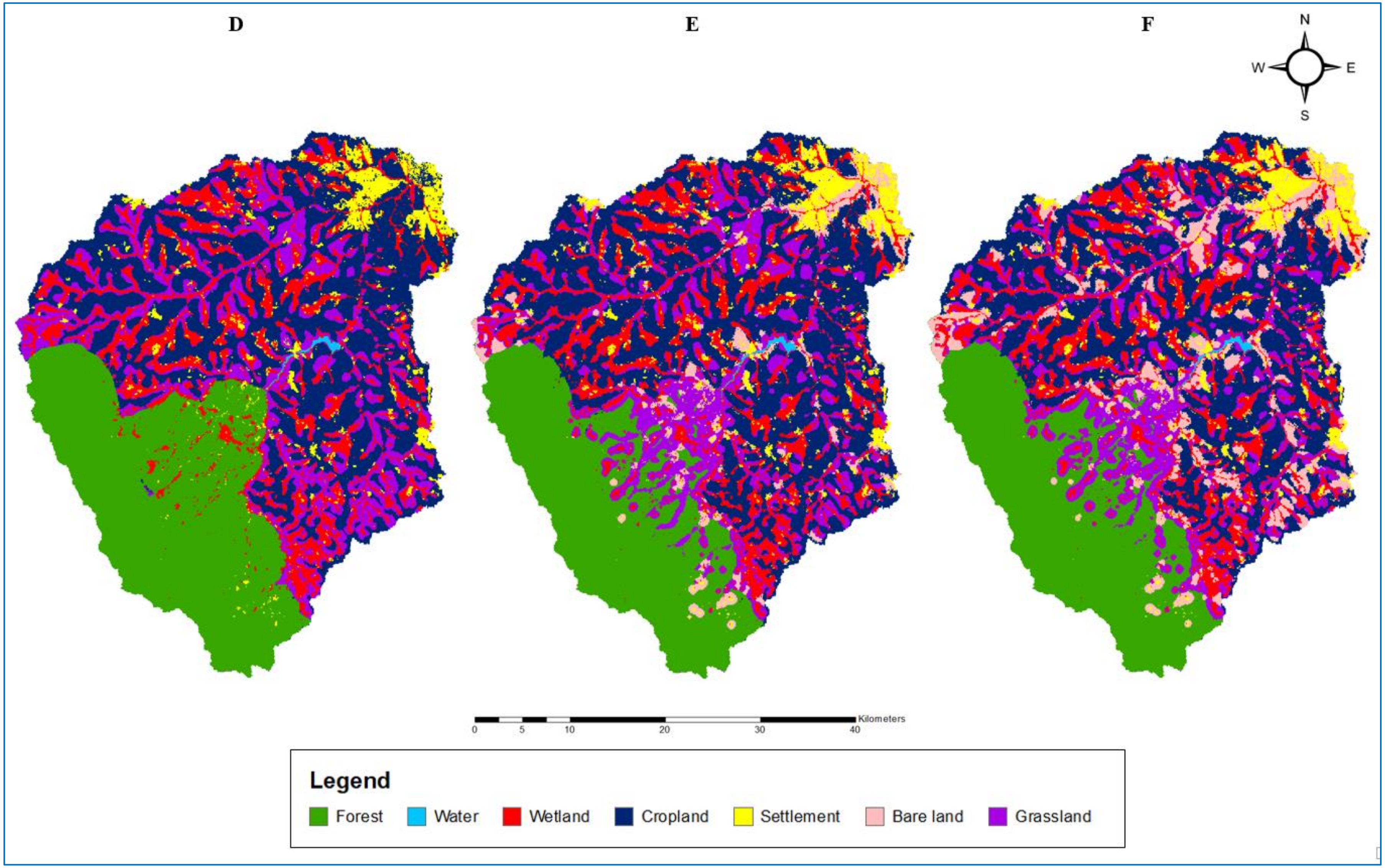

Figure 4.17: Potential land use scenarios **D**, **E**, and **F** proposed for Lilongwe River Catchment.

4.3 Lilongwe River Regime Under Different Land Use Scenarios

4.3.1 Effect of Different Land Use Patterns on Streamflow

Figure 4.18, Figure 4.19 and Figure 4.20 chart the projected flows from the 21 land use and RCM scenario combinations in the dry season, wet season, and annual time frame. The first 18 of the 21 flow outputs presented in each chart resulted from the use of the proposed land use maps and RCMs as input in SWAT, while the latter 3 show outputs from the current streamflow regime determined in Objective 1.

Results from the dry season depicted in Figure 4.18 show that increased flows were achieved by most proposed land use scenarios. Table 4.11 presents statistics describing these results and shows that the maximum positive change in flow in the dry season was 0.1 m^3/s. This projection resulted from the combination of Land Use Scenario E (which featured +100 % Grassland, and +100 % Bare land) and the MPI-CSC-REMO2009 and therefore amounts to +8 % of the current projected streamflow from that RCM scenario. No negative changes in dry season flow were registered.

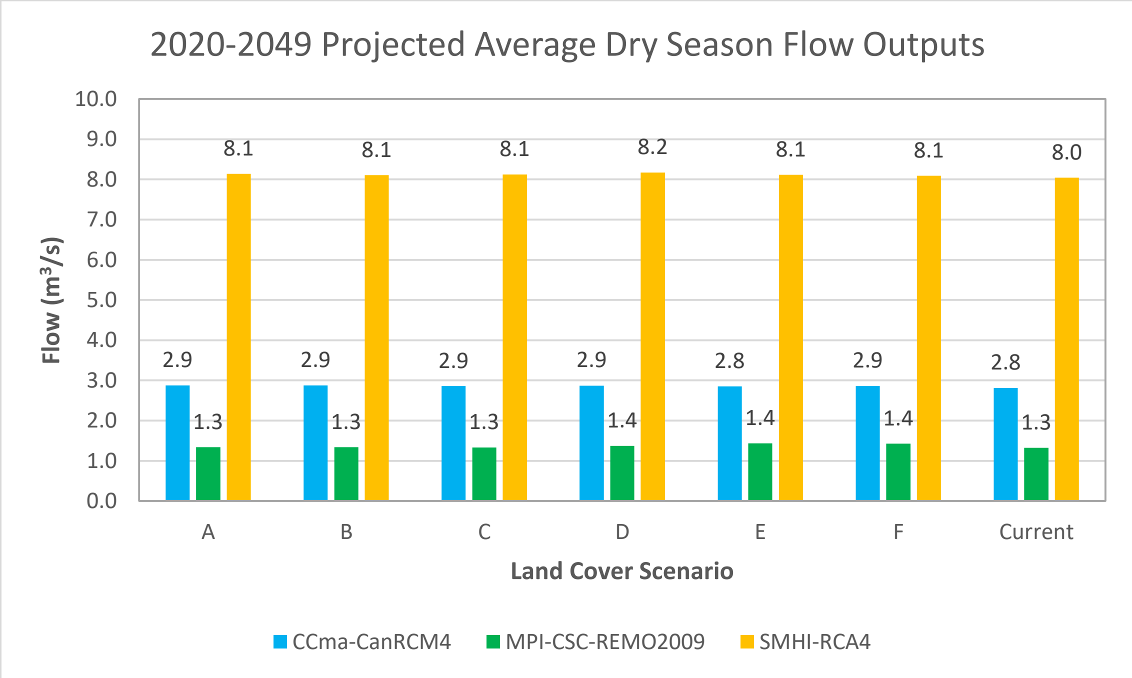

Figure 4.18: Average dry season flow outputs for 2020-2049 period from RCMs and proposed land use scenario data.

Lilongwe River flow in the wet season was also projected to increase as a result of most of the proposed land use scenarios, albeit by smaller percentages than in the dry season as shown in Table 4.11. The maximum positive change was registered also from the Scenario E and MPI-CSC-REMO2009 combination amounting to 0.8 m^3/s, +3 % of current flow from the same RCM scenario. Negative changes were also registered with the maximum resulting from the Land Use Scenario C (which featured +100 % Settlements and +50 % Grassland) and MPI-CSC-REMO2009 combination amounting to -0.3 m^3/s or -1.4 % of current flow projections.

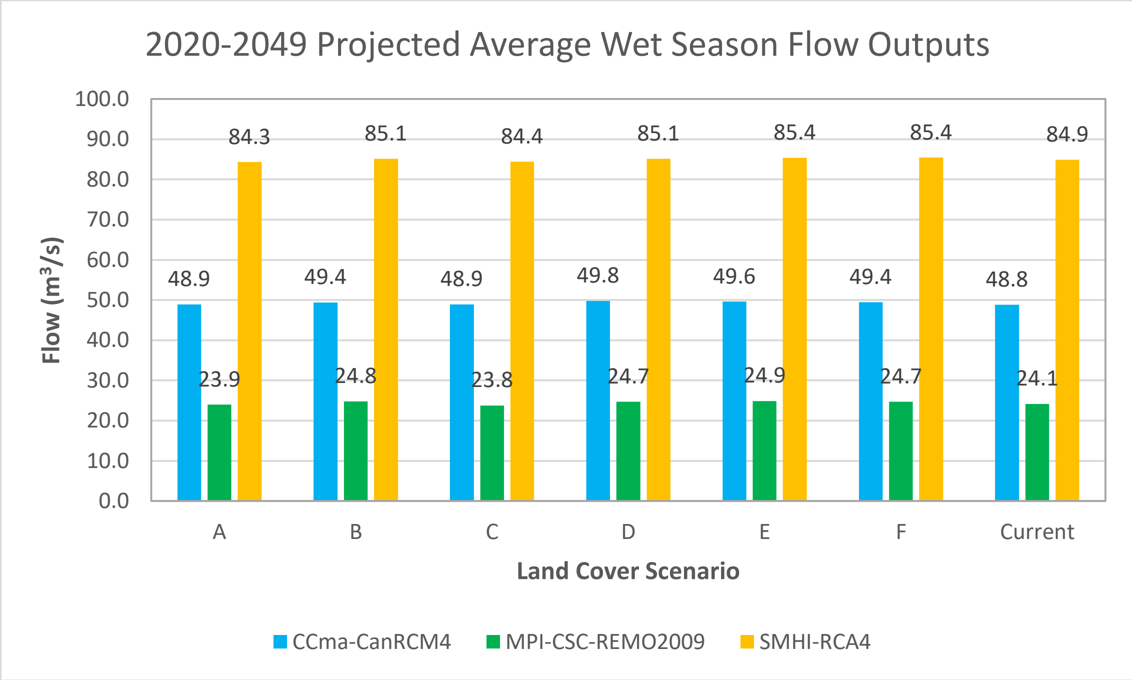

Figure 4.19: Average wet season flow outputs for 2020-2049 period from RCMs and proposed land use scenario data.

The land use scenarios also produced mixed results on an annual time scale as presented in Table 4.11. Maximum positive flow changes from the Land Use Scenario E and MPI-CSC-REMO2009 projection registered an increase of 0.5 m^3/s in annual flow (+4 % of the current flow projection). A maximum negative flow change of -0.1 m^3/s (-1.1 %) also resulted from the Land Use Scenario C and MPI-CSC-REMO2009 projection.

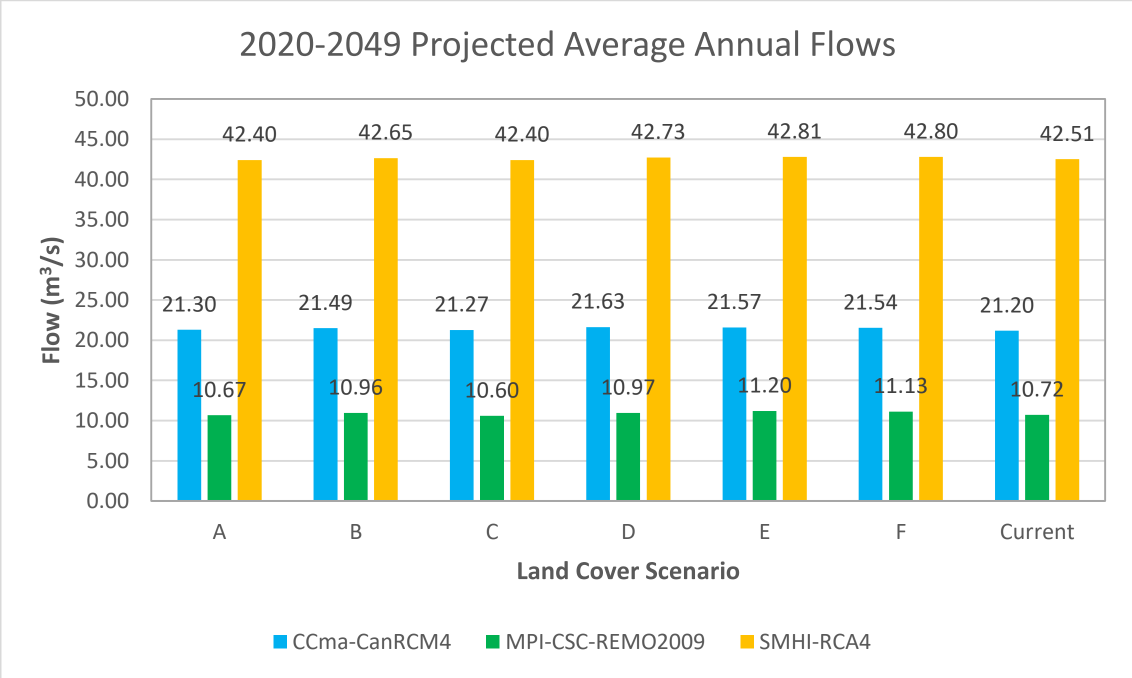

Figure 4.20: Projected average annual flow outputs for 2020-2049 period from RCMs and proposed land use scenario data.

Overall, results show that the differences in current projected flow and that from the proposed land use scenarios are small, with standard deviation between the outputs only varying between 0.01 and 0.05 m^3/s in the dry season, and 0.4 to 0.5 m^3/s in the wet season. Assuming all flow output data were normally distributed, this means that 95 % of all flow changes were less than or equal to 0.1 m^3/s and 1 m^3/s in the dry and wet season respectively.

4.3.2 Land Use Scenarios Yielding an Ideal Streamflow Regime

Figure 4.21 and Figure 4.22 present simplified flow duration curves created from the SWAT simulation flow output of each RCM and land use scenario combination. The charts show that no land use-RCM combination resulted in flow output that exceeded the 100-year flood threshold of 784.45 m^3/s with a probability of more than 1% which was defined as the ideal streamflow regime upper limit. Despite this positive outcome, the curves show that none of the 18 land use-RCM combinations would result in an ideal streamflow regime. No land use-RCM combination resulted in flow output that exceeded the 2049 projected water demand of 5 m^3/s with a probability of more than 99 %, which was defined as the ideal streamflow regime's lower limit. In fact, the curves show none of the combinations would exceed the projected water demand threshold with a probability of more than 75 %. Results also show that changes in land use pattern would not be able to increase flow beyond the projected 0 m^3/s at 90 % probability in the MPI-CSC-REMO2009 climate scenario.

Table 4.11: Projected dry season, wet season, and annual flow average flow output for 2020-2049 period from RCMs and land use scenario data.

	Average Dry Season Flow Projections			Average Wet Season Flow Projections			Average Annual Flow Projections		
Scenario	**CCma-CanRCM4**	**MPI-CSC-REMO2009**	**SMHI-RCA4**	**CCma-CanRCM4**	**MPI-CSC-REMO2009**	**SMHI-RCA4**	**CCma-CanRCM4**	**MPI-CSC-REMO2009**	**SMHI-RCA4**
A	2.9	1.3	8.1	48.9	23.9	84.3	21.30	10.67	42.40
B	2.9	1.3	8.1	49.4	24.8	85.1	21.49	10.96	42.65
C	2.9	1.3	8.1	48.9	23.8	84.4	21.27	10.60	42.40
D	2.9	1.4	8.2	49.8	24.7	85.1	21.63	10.97	42.73
E	2.8	1.4	8.1	49.6	24.9	85.4	21.57	11.20	42.81
F	2.9	1.4	8.1	49.4	24.7	85.4	21.54	11.13	42.80
Current	2.8	1.3	8.0	48.8	24.1	84.9	21.20	10.72	42.51
Average:	2.9	1.4	8.1	49.3	24.5	84.9	21.5	10.9	42.6
Average Change (%):	2	4	1	1	1	0	1	2	0
Standard Deviation:	0.01	0.05	0.03	0.4	0.5	0.5	0.1	0.2	0.2
Minimum:	2.8	1.3	8.1	48.9	23.8	84.3	21.3	10.6	42.4
Difference of Min to Current	0.0	0.0	0.0	0.1	-0.3	-0.6	0.1	-0.1	-0.1
Difference of Min to Current (%)	1.2	0.4	0.6	0.2	-1.4	-0.7	0.4	-1.1	-0.3
Maximum:	2.9	1.4	8.2	49.8	24.9	85.4	21.6	11.2	42.8
Difference of Max to Current	0.1	0.1	0.1	1.0	0.8	0.5	0.4	0.5	0.3
Difference of Max to Current (%)	2	8	2	2	3	1	2	4	1

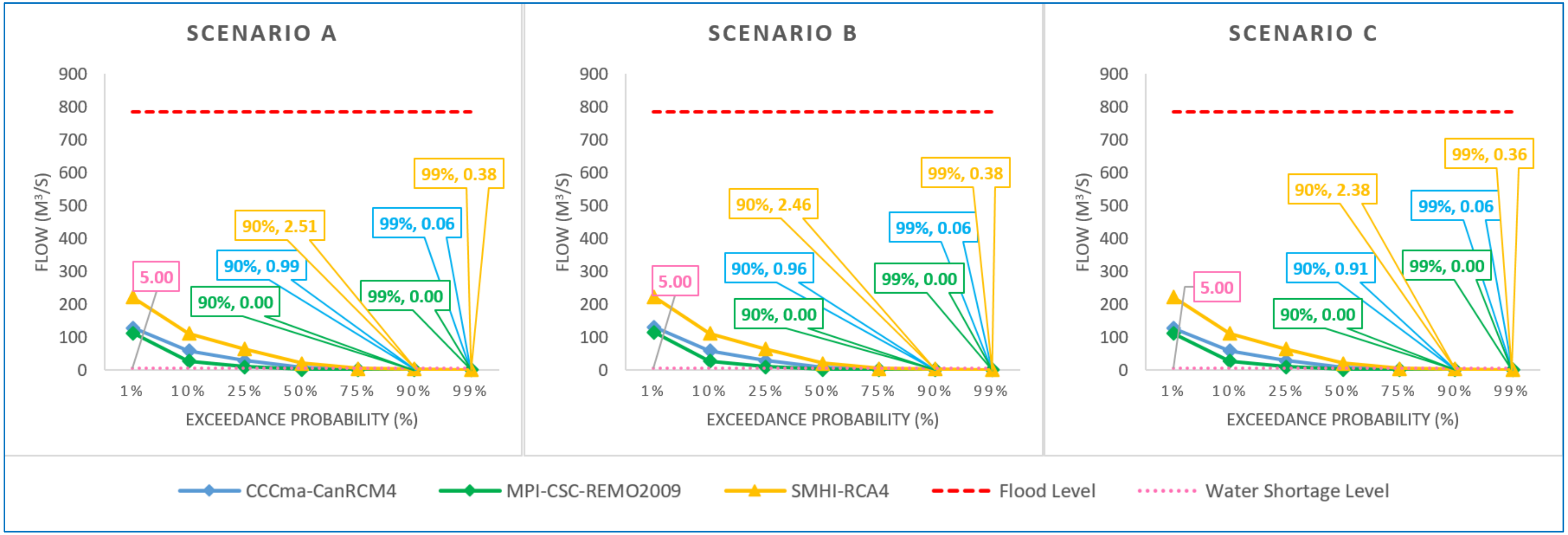

Figure 4.21: Simplified flow duration curves of output from each RCM and proposed land use scenarios A, B, and C.

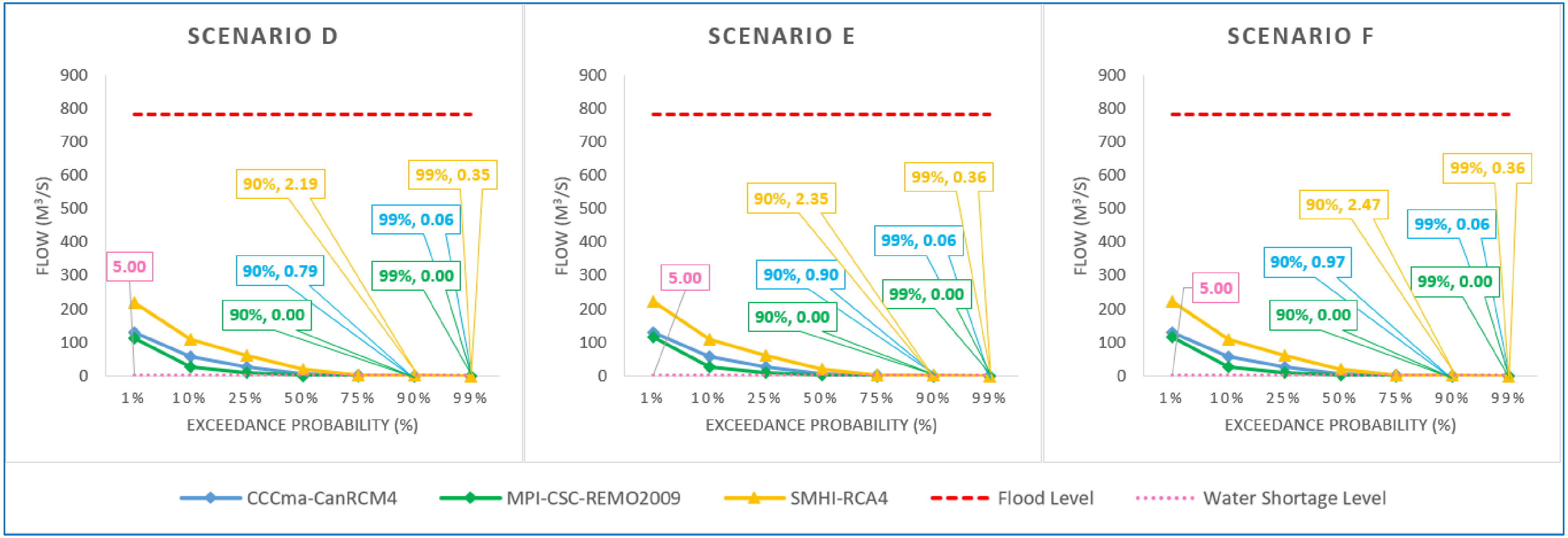

Figure 4.22: Simplified flow duration curves of output from each RCM and proposed land use scenarios D, E, and F.

CHAPTER FIVE: DISCUSSION

5.1 Current Lilongwe Streamflow Regime

5.1.1 Current Land Cover

The study first set out to establish the land cover pattern which currently influences the flow regime of the Lilongwe River. Results showed that the majority of land area in the catchment is dominated by cropland which covers 45.83% of the total area, followed by forests at 32.59%, then wetlands/grassland, settlements/bare land, and water (Table 4.1). These findings were not only verified by the accuracy assessment exercise but are also consistent with the findings of FAO (2012) in terms of spatial distribution of the classified land cover types. The FAO study however, was conducted at the district level and, therefore, could not facilitate direct numerical comparison of area proportions covered by the different land cover types in the Lilongwe River Catchment alone.

The results, among other things, portray the prevalence of smallholder subsistence farming in Lilongwe District and the nation at large (Chirwa & Matita 2012; USAID 2017) with large swaths of land in the study area being dominated by small fields of crops such as maize. Wetland and/or grassland areas on the other hand were often found along river banks where soil moisture is abundant. Cultivation along these banks or on the river bed was also observed to be common which is not only illegal (GoM 2013), but also increases the risk of soil erosion, pollution, and damage to the crops from flooding (Chimwanza, Mumba & Kadewa 2006; Zidana *et al.* 2007; Mlowoka 2012). The results also confirm that large areas of previous forest, bare land, and grassland in the catchment have mostly been converted to cropland or settlements in the past few decades (Munthali & Murayama, 2011; Munthali 2013; Sibande *et al.* 2020) with the most significant patch of forest conserved in the Dzalanyama Forest Reserve.

Results of the study also evidence the capability and versatility of machine learning algorithms (SVM in particular) in classifying medium resolution satellite imagery with relatively small training data sample sizes (Maxwell *et al.* 2018). With an overall classification accuracy of 91.5%, the results of the accuracy assessment are comparable or better than those achieved using high resolution imagery and other advanced remote sensing techniques (Mutuku *et al.* 2009; Fichera, Modica & Pollino 2012; Zhao *et al*. 2017). Furthermore, results also showcase the practicality of using high resolution Google Earth images in collection of SVM training data by producing a classification accuracy comparable to that of physical observation-based referencing data (Mutuku *et al.* 2009; Fichera *et al.* 2012; Jin *et al.* 2014).

It is worth highlighting that errors in land cover classification were also present in this assessment as is common in most land cover detection studies. Causes of these errors included the close spectral similarity of some land cover features such as bare land to dry cropland, as well as the proximity of large swaths of one type of land use, such as cropland, to small patches (less than 900 m^2) of other land use classes, such as settlements.

5.1.2 Climate Projections

Analysis of climate projections was conducted to gain insight into how climatic conditions in the catchment may vary over the study period and consequently how this will affect streamflow. Results show that precipitation projections from the selected RCMs are ambiguous as some RCMs projected higher precipitation amounts in the catchment while others projected lower precipitation. These findings echo the assertions made by Vincent *et al*. (2014), and Stevens and Madani (2016) who argued that Malawi's future rainfall patterns are uncertain as there were no definitive trends established in either studies. It is therefore currently unclear as to whether future average rainfall amounts in the catchment will actually increase or decrease (Vincent *et* *al*. 2014; Adhikari & Nejadhashemi 2016; Stevens & Madani 2016). Considering this ambiguity, and the gradual nature of climatic changes (IPCC 2014; Chan 2018), it is unlikely that drastic increases projected in rainfall (especially by the SMHI-RCM4 model) would occur between 2020 and 2049. It is worth noting, however, that all RCMs used in this study projected record rainfall events surpassing those that occurred in the historical record of 1990 to 2019 (Table 4.3). This would likely lead to very high flows in the Lilongwe River and possibly cause severe flooding in the catchment.

Trend analysis of both minimum and maximum temperatures in the Lilongwe River Catchment also yielded mixed (Table 4.4). However, analysis of ensemble average minimum and maximum temperature projections predict an increase of 0.94 ℃ and 2.46 ℃ respectively. These figures are especially noteworthy since they present an ensemble average from across multiple models which, according to Warnatzsch and Reay (2018), is most accurate in predicting temperature in the region. These findings are also in agreement with most climate change assessments conducted in Malawi which assert that temperatures in Lilongwe and the country at large will continue to rise for the foreseeable future due to global warming (Msowoya *et al*. 2014; Vincent *et al*. 2014; Adhikari & Nejadhashemi 2016; Stevens & Madani 2016). Though exact figures differ, several studies estimate that average minimum and maximum temperatures in the region will likely rise between 1 ℃ and 2.9 ℃ respectively by mid-century (Msowoya *et al*. 2014; Vincent *et al*. 2014; Adhikari & Nejadhashemi 2016; Stevens & Madani 2016).

Temperature affects the hydrological cycle by increasing rates of evapotranspiration and thereby reduces the amount of water that infiltrates into aquifers or flows into streams (Gregory *et al.* 2009; Bethea 2011). Increased temperature may therefore exacerbate the water stress situation predicted to occur in the catchment (World Bank 2017). It is important to remember that these results do not reflect the exact values of weather data expected to occur in the Lilongwe River Catchment, but rather they give insight into the range of possibilities that need to be considered by decision-makers.

5.1.3 Flow Regime Projections

Despite the ambiguity in rainfall projections, RCM-driven SWAT outputs analysed in this study predicted flow increases in the wet and dry season ranging between 3 % and 263 %, and 4 % and 528 % respectively. All RCM-driven flow outputs predict increased streamflow in the wet season. It is important to note however that the flow duration curves presented in Figure 4.9 reveal that flooding beyond the 100-year threshold of 784.44 m^3/s is still a rare occurrence for the Lilongwe River.

Flood risk is the result of the interaction of three elements, these are: hazard, exposure, and vulnerability (Barredo & Engelen, 2010). The results in Figure 4.9 therefore suggest that the recent flooding disasters that occurred in Lilongwe (MSF-GIS Unit 2017; UNICEF 2017) may not necessarily have been the result of increased flood magnitudes or frequency (the hazard), but rather the exposure of lives and property to disaster prone areas. Proving this assertion is beyond the scope of this study and currently difficult since barely any flow records beyond the year 2000 exist for the Lilongwe River. However, several observations by the researcher, as well as accounts from officials from NWRA noted that river buffer zones in the catchment are neither well established nor enforced. As a result, many district residents have constructed structures or cultivate within the purported buffer zones and even on the actual river beds. This is particularly concerning since all projected flow outputs predict high magnitude floods to occur in the catchment over the next 30 years. A significant number of lives and property is therefore still under threat from potential flooding disasters in the catchment.

Results showed that average streamflow during the dry season is projected to increase in the river. This could help to alleviate the projected water shortages in the catchment which forecast peak water demand from the utility to increase from the current 2.265 m^3/s to 4.997 m^3/s by 2049 as shown in Section 4.2.1. However, results also show flows during the dry season are projected to fall far below the 2049 demand even in the SMHI-RCM4 high flow scenario. This highlights one of the problems being addressed by this study as current water demand is already forcing LWB to ration water supply to some parts of the city (World Bank 2017). The projected increase in demand will therefore not only cause massive water shortages for the city but also make it more difficult for the utility to release adequate environmental flows downstream of the LWB abstraction point.

Environmental flows are vital for the maintenance of a river's riparian ecosystem and therefore their absence could place its valuable components under threat. According to officials from NWRA, and GoM (2014), it is the Malawi government's policy that streamflow at 90 % exceedance probability (Q90) is the minimum amount of water that should be released from rivers for maintaining their vital ecosystem services. This policy is flawed for several reasons but one of the most obvious of all is that the policy applies even in cases where no flows occur at Q90. In other words, if a river dries up at 90 % exceedance probability, users are not obligated to release any water to the environment. Observed flow records for the Lilongwe River show that its Q90 amounted to 0.4 m^3/s for the period between 1962 and 1991, however, if the MPI-CSC-REMO2009 scenario projection is to be realised, this amount would soon equal to 0. This is because as a result of human activities such as damming of the river, and other hydrological processes, no water is projected to flow in the river about 10% of the time in that scenario. This would have adverse effects on the river's riparian ecosystem as well as informal downstream users.

As echoed by JICA (2014), these findings highlight the need for the establishment of detailed official guidelines for determining environmental flows in Malawi. No guidelines currently exist and, with the inevitable changing climate and other catchment conditions, their absence may lead to neglect or inequitable water access for some vital users. Adoption of systematic and adaptive techniques of water use planning, therefore, have to be promoted to ensure prudent use of the resources.

Overall, the analysis of flow projections revealed that all RCM scenarios would result in increased annual average streamflow ranging between 0.6 m^3/s and 42.5 m^3/s. This streamflow however is not available uniformly throughout the year and therefore must be stored to satisfy water demand at all times. Kamuzu Dam 1 and 2 were constructed for this very purpose, but LWB projections indicate that the dams' current storage capacity would not be adequate to meet future demand. Other than increasing storage capacity or exploring a new source, increasing the river's minimum natural streamflow through land use management was therefore examined as one other supply-side solution to the problem as discussed in the following sections.

5.2 Practical Land Use Scenarios for the Lilongwe River Catchment

5.2.1 Effect of Land Cover Classes on Flow

The effects of each land cover class identified in the study area on flow in the Lilongwe River were examined. Results of the analysis showed promise in the land use and streamflow management concept as a solution to the water shortage problem facing Lilongwe with changes in streamflow as high as 85 %. The results shown in Figure 4.12 and Figure 4.13 indicated the largest positive increase in flow resulted from bare land during the wet season. Figure 4.14 and Figure 4.15 further show that this increase was as a result of high runoff and low infiltration and evapotranspiration rates. This is consistent with other studies which argue bare land offers little resistance to runoff to facilitate infiltration after a precipitation event and hence the water easily flows into rivers, creating high discharge (Palamuleni 2009; Geremew 2013). The absence of features such as vegetation or buildings on the land also reduces the surface area from which interception and evapotranspiration can occur and thus increases the amount of water available to flow into the river (Brutsaert 2005; Gerrits 2010).

One surprising finding was that bare land also resulted in high flows during the dry season in the CCma-RCM4 and MPI-CSC-REMO2009 climate scenarios. This is counter-intuitive since bare land is often understood to cause high amounts of direct runoff and as a result, very little water is available to replenish rivers through baseflow during the dry season (Palamuleni 2009; Roa-García *et al.* 2011; Geremew 2013; Guzha *et al.* 2018). Although Figure 4.14 and Figure 4.15 show that baseflow is indeed reduced by bare land in the catchment, they also reveal that baseflow accounts for a very small part of the average dry season streamflow in the catchment. This is likely due to the operation of the two dams on the river which release water during the dry season, along with the increased runoff, reduced interception, and evapotranspiration losses that typically result from bare land cover.

Figure 4.12 and Figure 4.13 also showed that a full catchment of grasslands would contribute to higher flow in the Lilongwe River than the current land cover pattern in both the wet and dry seasons. Based on the results Figure 4.14 and Figure 4.15 this may also be because grasslands offer less resistance to runoff than cropland or trees, depending on the type of grass in question (Li *et al.* 2017). The low interception and water uptake levels known to be exhibited by grass as compared to trees and some types of crops may also aid in increasing streamflow (Adane *et al.* 2018).

Another key finding from the analysis was that forest land cover caused flow reductions in the catchment in both the wet and dry seasons. Forests are often understood to reduce runoff and increase infiltration in a catchment and thereby reduce flow in the wet season, but increase the amount of water available for underground flow into rivers during the dry season (Geremew 2013; Kabombe *et al*. 2018; Nkhoma *et al.* 2020). This idea is otherwise known as the infiltration-evapotranspiration trade-off hypothesis which postulates that dry season flow in an area is reduced when vegetative cover is removed because water infiltration and soil storage that normally replenishes the river is impaired during the wet season (Roa-García *et al.* 2011; Cingolani *et al*. 2020). As illustrated in Figure 4.14 and Figure 4.15, results indicate that the Lilongwe River Catchment is not defined by this hypothesis.

Simulation outputs from the homogenous forest land map revealed that high evapotranspiration from trees causes severe reductions in water in the catchment in both the wet and dry seasons as a large number of trees in the catchment are non-deciduous. Other than increasing the surface area on which interception may occur (Gerrits 2010; Adane *et al.* 2018), these trees take up substantial quantities of subsurface water especially in the dry season which is then removed from the catchment through wind action and transpiration. As a result, Figure 4.15 shows that the hypothesized increase in baseflow is almost non-existent during the dry season, whilst it is reduced during the wet season when compared to that produced by the current land cover.

The Lilongwe River Catchment is but one of many catchments which are not characterised by the infiltration-evapotranspiration trade-off hypothesis. Several studies including those by Scott *et al.* (2004), Jewitt *et al.* (2004), and Levy *et al.* (2018) similarly concluded that forest cover reduced flows in both the wet and dry seasons in their respective study areas. Scott *et al.* (2004) in particular noted that experiments conducted in South Africa showed water uptake by tree crops sometimes exceeded annual rainfall. Explanations for these reductions vary depending on the region, but one major factor that influences infiltration and baseflow in the Lilongwe River Catchment may be the slope of the catchment which is relatively flat and thus infiltration rates are unlikely to drastically change based on the land cover. Another reason could be the hydrogeology of the catchment where the position of aquifers may have greatly influenced the amount of water flowing into streams through baseflow.

All in all, results of the land-flow analysis confirm that substantial changes to streamflow are possible in the catchment depending on the land use or cover established in the area. However, results also suggest that weather differences such as temperature, rainfall frequency, and rainfall intensity are the biggest factors that influence streamflow in the catchment. This is evidenced by the clear difference between flow outputs resulting from the homogenous land cover maps and that between flow outputs from different RCM projections which were much larger in comparison. This observation has been echoed by many researchers who assessed the impacts of climate versus land use on streamflow in underdeveloped catchments such as that of the Lilongwe River (Calder *et al.* 1995; Guo *et al.* 2014; Chawla & Mujumdar 2015; Pervez & Henebry 2015; Nkhoma *et al*. 2020). Guo *et al*. (2014) for instance noted that land use changes over 10 years in a study catchment in China reduced streamflow by 3 mm while slight changes in climate reduced runoff by 23 mm in the same period. Similar results were found in the current study with the vast majority of variations in flow simulation output notably due to the difference in climate data used. The effects of each land cover class can therefore best be described based on each RCM scenario separately.

5.2.2 Proposed Land Use Scenarios

Six land use scenarios were developed with the main aim of increasing streamflow in the Lilongwe River since flooding was projected to remain a rare occurrence, but water shortage would continue to be a problem (Figure 4.16 and Figure 4.17). Each land use scenario developed was steeped in reality and was based on assumptions that can be realised in the catchment either naturally or by policy intervention. Development of Scenarios A, B, C, and F for example, capitalised on trending changes in land use expected in the catchment such as rapid growth of settlements (Manda 2015) especially with the district’s population projected to grow by 59 % by 2043 (NSO 2020).

Grass often naturally grows in areas with low human activity, including river banks, cropland, and protected areas, hence Land Use Scenarios C, D, E, and F could occur naturally or with minimal policy intervention. Bare land can expand in the course of preparing land for the development of new settlements or as a result of deforestation. Land Use Scenarios E and F were especially developed consistent with the findings of Munthali (2013) who revealed that deforestation in Dzalanyama Forest Reserve is a constant challenge mainly due to the need for fuel wood by residents of nearby settlements, and the illegal charcoal industry persistent across Malawi. As a result, Munthali (2013) predicted the Dzalanyama forest reserve could lose up to 26,721 hectares of forest by 2030. An increase in population and therefore settlements would likely exacerbate deforestation in the reserve if no firm action is taken to curb this problem, and hence Land Use Scenario F could very well become reality.

5.3 Effect of Land Use Scenarios on Streamflow Regime

5.3.1 Effect of Different Land Use Patterns on Streamflow

Each land use map created in Objective 2 was used as input for SWAT to produce the output summarised in Table 4.11 and illustrated as flow duration curves in Figure 4.21 and Figure 4.22. Results showed that the projected flow in the river would vary depending on the RCM and land use scenario combination realised in the catchment. They also showed that land use scenarios that featured larger amounts of bare land, grassland, and settlements (Scenarios D, E, and F) produced the highest increases in flow during the wet and dry season, as well as annually. From the land use perspective, this finding is in agreement with the observation made in the previous sub-section that bare land and grasslands result in the highest flow increases in the catchment. As previously mentioned, this is likely because bare land and grasslands provide little resistance to runoff and transpiration losses as compared to the current land cover pattern in the catchment. In reference to the water budget, this theoretically then leaves more water available for runoff or lateral flow to occur, and hence streamflow amounts are often high (Adane *et al.* 2018; Guzha *et al.* 2018).

Using the different land use scenarios as SWAT input, Table 4.11 shows that a maximum percentage change of +8 %, +3 %, and +4 % was observed in simulated streamflow output from the dry season, wet season, and annually respectively. These flow changes are proportionally similar to the flow or runoff changes reported by other similar studies such as Evelyn (2009) (between -5 % and -24 %), Memarian (2016) (-2.76 %), and Yini *et al*. (2016) (between -2.7 % and -17.6 %). However, it is important to note that each of these studies aimed to reduce peak flows or runoff and thus were conducted only to address problems associated with high river flows such as flooding or sedimentation. This is in contrast to the current study which, other than to prevent flooding, also sought to study how low flows can be increased in the catchment. In fact, to the best of the researcher's knowledge, few if any studies had ever been conducted aiming to increase streamflow through land use planning. The findings in the current study therefore not only confirm that LUC re-patterning can facilitate positive and intentional changes in streamflow, but also highlight a novel or seemingly overlooked option for addressing water shortage problems.

5.3.2 Land Use Scenarios Yielding an Ideal Streamflow Regime

Despite all land use-RCM combinations meeting the upper limit criteria of the ideal streamflow regime defined previously (i.e. < 784.44 m^3/s), results definitively show that the land use-RCM combinations tested are unlikely to yield significant flow increases in the river that would surpass the lower limit (i.e. > 5 m^3/s, see Figure 4.21 and Figure 4.22). In truth, looking at the flow duration curves in Figure 4.21 and Figure 4.22, the ideal streamflow regime lower limit is actually only surpassed once beyond 75 % exceedance probability in the Land Use Scenario C and SMHI-RCM4 combination. Therefore, none of the proposed land use scenarios would yield an ideal streamflow regime for the Lilongwe River. Although attempts to reduce peak flows and runoff through LUC re-patterning have proved successful by other studies (Evelyn 2009; Zhang *et al.* 2014; Yini *et al*. 2016; Tajbakhsh *et al.* 2018), few if any studies have attempted to explore the same towards increasing streamflow, hence comparisons on that front are difficult to make.

One key finding from this study is that some increases in streamflow could still occur upon adoption of the proposed land use patterns, with the highest increases of up to 0.8 m^3/s occurring during the wet season. Considering the 2049 projected daily demand of 5 m^3/s, this increase in flow would fully satisfy demand from the river in about 1 out of every 6 days. The average annual flow increase of 0.5 m^3/s projected by one land use-RCM combination could also satisfy demand in 1 out of every 10 days. Therefore, despite not meeting the threshold set in this study, the projected flow changes from the different land use-RCM combinations could have a real positive impact on not only people's lives in the catchment but also on that of the many riparian organisms that are sustained by the river.

It is worth noting that the assertions made in this study were limited to the low emissions (RCP4.5) climate scenario projections. Results of high emission scenarios may therefore differ and, if predictions by most climate change studies based on these scenarios are correct, would likely lead to more extreme weather events and streamflow events (IPCC 2014; Seyoum 2017; Serdeczny *et al*. 2017; Girvetz *et al.* 2019).

All in all, as expressed by other studies (World Bank 2017, GoM 2020), the findings of this study highlight the fact that Lilongwe City will soon outgrow the capacity of Lilongwe River as a source of water. With a projected population of 1.6 million by 2043

(NSO, 2020), water demand from the city and its surrounding areas will simply become too great to be substantially addressed by any land use interventions. Furthermore, potential increases in streamflow can only be useful if beneficiaries of the river can access them as required. Since the Kamuzu dams have limited capacity, high flows in the river often quickly drain downstream and ultimately into Lake Malawi without being used by Lilongwe's residents. It is, therefore, of utmost importance that decision-makers take appropriate actions to increase the water storage capacity in the catchment, or to develop alternative sources of water to supply the city.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study aimed at examining the concept of land use or cover re-patterning as a method of modifying streamflow regime in the Lilongwe River Catchment. This was done by first establishing the current land cover pattern and projecting the current streamflow regime of the Lilongwe River from 2020 to 2049 through a combination of remote sensing techniques, as well as climate and hydrological modelling. New practical land use scenarios for the Lilongwe River Catchment were then developed through land use modelling and based on a defined ideal streamflow regime, literature review, and legal and institutional frameworks. The effect of each land use scenario was then examined to determine if any pattern could yield the aforementioned ideal streamflow regime.

Results show that water shortages between 2020 and 2049 and will continue to become more common in the catchment unless mitigation measures are taken, but severe flooding will remain a very rare occurrence. Results also revealed that at least six practical land use scenarios for the catchment can be adopted to increase streamflow in the Lilongwe River. However, the study concludes that LUC re-patterning may not be a viable method for modifying streamflow in the Lilongwe River Catchment as none of the different land use scenarios examined would adequately increase streamflow to satisfy the 2049 water demand.

6.2 Recommendations

The following are recommendations that are made based on the findings of this study:

- New water sources along with the necessary associated facilities such as storage tanks and conveyance systems must be developed for the catchment to cater for the growing water demand.
- The study implores the Malawi Government to formulate legislation that considers the impacts of land use practices on streamflow. Such a development could help mitigate the ill effects of LULCC and prevent exacerbation of the already dire water shortage situation in the Lilongwe River Catchment.
- Further research is recommended to establish if land use modification can be used to manage streamflow in other catchments since hydrological responses to LULCC vary based on individual catchment characteristics. Ideal streamflow requirements also vary between catchments and therefore land use modification may more easily achieve intended results.

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APPENDICES

8.1 Appendix 1: Kamuzu Dam 1 and 2 SWAT input parameters

Variable Name	Description	Kamuzu Dam 1 Input	Kamuzu Dam 2 Input
MORES	Month the reservoir became operational	Start of simulation	May
IYRES	Year the reservoir became operational	1965	1989
RES_ESA	Reservoir surface area when the reservoir is filled to the emergency spillway (ha)	138	287.5
RES_EVOL	Volume of water needed to fill the reservoir to the emergency spillway ($10^4 m^3$)	522.5	1933
RES_PSA	Reservoir surface area when the reservoir is filled to the principal spillway (ha)	10.71	27.5
RES_PVOL	Volume of water needed to fill the reservoir to the principal spillway ($10^4 m^3$)	71.43	44.44
RES_VOL	Initial Reservoir volume	71.43	44.44
RES_SED	Initial sediment concentration in the reservoir (mg/L)	1300	1300
RES_NSED	Equilibrium sediment concentration in the reservoir (mg/L)	1300	1300
RES_D50	Median particle diameter of	10	10

	sediment (μm)		
RES_K	Hydraulic conductivity of reservoir bottom	0.4	0.4
EVRSV	Lake evaporation coefficient	0.6	0.6
IRESCO	Outflow simulation code	Simulated target release	Simulated target release
RES_RR	Average daily principal spillway release rate (m^3/s)	9.7	9.8
IFLOD1R	Beginning month of non-flood season	October	June
IFLOD2R	Ending month of non-flood season	October	October
NDTARGR	Number of days to reach target storage from current reservoir storage	60	80
WURTNF	Fraction of water removed from the reservoir for consumptive use that is returned and becomes flow out of reservoir (m^3/m^3)	0	0
OFLOWMN_FPS	Minimum reservoir outflow as a fraction of the principal spillway volume	0	0
STARG_FPS	Target volume as a fraction of the principal spillway Volume	1	1

8.2 Appendix 2: Key Informant Interview Transcripts

8.2.1 Key Informant Interview 1: Principal Estate Management Officer – Mr. T. Mwale

Who is responsible for land use planning in Malawi and how are development plans created?

"The Department of Physical Planning and Surveys (DPPS) is responsible for creation and approval of any land development plans in the country. In urban areas, they use the urban structure plan or land use plan for creating new plans which details the zonation of different parts of urban land as residential, commercial, or industrial etc. So when tasked with identifying land for any new project the DPPS first looks at the urban structure plan to determine whether the area was designated for such a development. Depending on the situation some areas designated for one land use type may be re-zoned to another when the department's priorities change."

When a new project is proposed does it come to the Department of Lands and Valuation for approval?

"Yes, when the time comes to perform actual land use allocation, we [the Department of Lands and Valuation (DLV)] are tasked with the job. For example, when people request to build residential houses in Area 43, we first send a request to the Department of Physical Planning for them to perform a perimeter survey, which they then use to prepare a detailed layout plan. This plan is what we then follow to allocate land accordingly to individual clients."

Does the Department of Physical Planning (DPPS) use any criteria in designating land use zones?

"I do not think they have a specific formula but what they do is make sure the land use plans are compatible with each other, and the land in question. For example,

commercial, residential, and industrial zones cannot be placed in the same exact area. The most important thing considered however is terrain, because it often determines the layout of developments. This is especially true for roads in terms of their design and for the sake their durability. Naturally, some allocation exercises disregard terrain a lot more in mountainous areas since there are few alternatives, such as in Blantyre, as compared to flat areas like Lilongwe. So compatibility is what is mostly considered for a city.

Additionally, Lilongwe for example is an administrative city, which is different from a commercial city like Blantyre. Being an administrative city, it is therefore more important to allocate more land for residential areas in Lilongwe as compared to Blantyre where commercial areas may be prioritised. In fact, looking at the current land use map of Lilongwe, you will notice there are few industrial areas because since the city was established it has been mainly utilized for administrative purposes."

Are any policies or legal directives used to guide allocation of land?

"The main guiding piece of legislation for allocation of land in the country is the National Physical Development Plan. It divides the country into national (e.g. Lilongwe), regional (e.g. Kasungu, or Karonga), sub-regional (e.g. Nkhotakota), and district centres (e.g. Dowa). The plan governs a lot of decisions, for example, say you apply to construct a hotel in Ntcheu, we (DLV) forward your application to DPPS to refer your application to the NPDP and if that area is not designated for a hotel, you would be advised to construct elsewhere. In case the area is indeed designated for such developments, the project implementer is informed of the building standards in accordance with the NPDP that they must agree to in order for the development to be approved."

Where are these land use planning standards specified?

"I suggest you get in touch with Mr. Lukasi for that who is the regional commissioner of the DPPS. He would show you everything including the NPDP, regulations and guidelines for development in both cities and urban centres. All these sets of information are available to guide planners, for example to specify that a new road within a specific residential area has to be say 12 meters. It is also the reason a lot of hospitals, police buildings, and teacher's colleges such as Nalikule, look similar because the standards used for their design are also the same. Regulations on developments near lakes, rivers, or other waterways are also specified in the guidelines."

Is it possible for DPPS to first get ideas of developments before land use allocation plans are made?

"It is possible."

Do you foresee any challenges with that mode of planning?

"No I do not believe there are any real challenges from the standpoint of the department, but the biggest challenge to such planning is politics. Sanctioning or denying of some developments has sometimes been influenced by political pressure despite the position of land departments being against the move in question. Sometimes projects are illicitly approved upon subversion of formal procedures such as Environmental Impact Assessments (EIA). However, barring the potential for such influences that mode of planning is very possible."

8.2.2 Key Informant Interview 2: *Acting Commissioner for Physical Planning – Mr. R. B. Lukasi*

1. **How do planners consider legal restrictions when producing new land use plans? For example, I understand buildings are not supposed to be built**

within a river's flood buffer zone. How do planners consider these during the planning process?

"Legal restrictions to land use allocation are applied based on existing legislation such as the Physical Planning Act, Environmental Management Act, Water Resources Act, and Physical Planning Regulations and Planning Standards and Guidelines. Detailed layout plans are then assessed environmentally and socially before being approved by responsible authorities. For example, the Water Resources Act restricts development in natural water courses including buffer zones. It also provides widths for river reserves depending on the historic flooding and slopes of the river banks."

2. **Is there a list of the laws, policies, or restrictions that the department uses to produce new land use plans?**

"In land use planning, there are basic principles that one needs to apply including international planning theories and concepts which are normally adapted to local situations. These however are applied in consonant with the existing policies, planning manuals, regulations and laws. In addition, a land use plan needs to be comprehensive as it also guides provision of infrastructure and social services in area. This is why a physical planner is not restricted to environmental laws only but also uses the Public Roads Act and national standards for social services such as health centres and schools."