

MAKERERE



UNIVERSITY

**IMPACT OF CLIMATE AND LAND USE LAND COVER CHANGE ON
WATER QUALITY IN SIRONKO CATCHMENT, MT. ELGON**

BY

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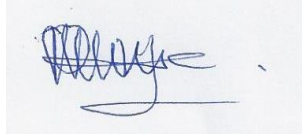
**A THESIS SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE
TRAINING IN FULFILMENT FOR THE AWARD OF THE DEGREE OF DOCTOR OF
PHILOSOPHY OF MAKERERE UNIVERSITY**

FEBRUARY, 2023

DECLARATION

I solemnly declare that this Thesis is my original work and where other people's or my own work has been used, it is properly acknowledged and cited. This work has never been submitted before, either in part or in full for any degree award or examination to any university or institution of higher learning.

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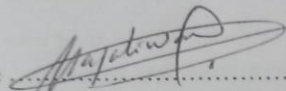


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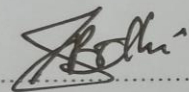
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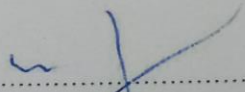
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DEDICATION

This work is dedicated to the following people for their unique contributions towards my education and family life:

1. My late brother Otim Denis Mukulu (R.I.P)
2. My late mother and father Acayo Jerolina Ojok and Ojok Selection (R.I.P)
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LIST OF ACRONYMS

Agricultural Model Inter-comparison and Improvement Project	AgMIP
Coefficient of Variation	CV
Digital Elevation Model	DEM
European Centers for Medium-Range Weather Forecast	ECMWF
Geographical Information System	GIS
Geographical Positioning System	GPS
Global Circulation Models	GCMs
Government of Uganda	GoU
Green House Gas	GHG
Gross Domestic Product	GDP
Hydrological Response Units	HRUs
Integrated Water Resources Management	IWRM
Internally Displaced Person's	IDP's
Land Change Modeler	LCM
Land Use and Land Cover Change	LULCC
Multi-Layer Perceptron	MLP
Ministry of Water and Environment	MWE
Modern Era-Retrospective Analysis for Research and Applications	MERRA
National Aeronautics and Space Administration	NASA
National Development Plan	NDP
National Environment Management Authority	NEMA
Office of the Auditor General	OAG

Operational Land Imager-Thermal Infra-Red Scanner	OLI-TIRS
Remote Sensing	RS
Representative Concentration Pathways	RPCs
Soil and Water Assessment Tool	SWAT
Standardized Precipitation Index	SPI
Uganda Bureau of Statistics	UBOS
Uganda National Bureau of Standards	UNBS
Uganda National Meteorological Authority	UNMA
Uganda National Roads' Authority	UNRA
United States Geological Survey	USGS

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ABSTRACT

Surface water quality underpins a range of livelihood means in Sironko catchment. This study determined the impacts of climate and Land use Land Cover Change (LULCC) on water quality in Sironko catchment. Field assessment of selected water quality from January to December 2018 followed standard procedures. Land use land cover change maps of Sironko catchment in 1986, 2000, 2016 and 2040 were developed by supervised classification. Baseline 1980-2009 and future climate scenarios 2025-2040 were downscaled by delta method. Stream flow, Total Suspended Solids (TSS), Total Nitrogen (TN), and Total Phosphorus (TP) loads were simulated using the Soil and Water Assessment Tool (SWAT). Mean values of selected water quality parameters were compared with the Uganda National Bureau of Standards (UNBS) guideline for clean surface water quality. t-test was employed at $p < 0.05$ level to determine any significant difference in water quality. Trends and trend magnitudes were determined using the Mann–Kendall trend test and Sen’s slope estimator. The contribution of climate and LULCs on stream flow, TSS, TN, and TP were computed using a second powered matrix regression model. Results show that agricultural lands; forests; and wetlands areas reduced by 8 %; 32 %; and 20 %, respectively between 1986 and 2000. But between 2000 and 2016, forests and wetlands areas increased by 84 % and 5 % while woodlands and agricultural lands decreased by 43 % and 13% respectively. From 2016 to 2040, built-up areas are projected to increase by 74 %; agricultural lands by 5 %; and grasslands by 2 %; while wetlands will decrease by 9 % and woodlands by 7 %. Less variability was detected in March, April and May (MAM) rainfall $20 < CV < 30$ while SON showed high variability $CV > 30$. Annual rainfall will increase at $p < 0.05$ in Kumi and Nakapiripirit stations between 2025 and 2040 while mean temperature showed increasing trends at $p < 0.05$ between 1980 and 2009 and between 2025 and 2040. In terms of water quality parameters, Fecal coliforms were above UNBS limit of drinking water quality while significant seasonal differences were detected at $p < 0.05$ for pH, EC, TP, and DO. Whereas the impacts of both climate and LULCC on River flow are both significant at $p < 0.05$ levels between 2025 to 2040, climate change is projected to increase River flow more than LLCC while the latter is projected to increase TN more than climate change under both RCP 4.5 and RCP 8.5. Local communities should improve on their waste disposal mechanisms while they also adapt to and mitigate the impacts of climate and land use change on water quality in Sironko catchment.

CHAPTEONE: INTRODUCTION

1.1 Introduction

The impacts of future climate and Land Use Land Cover Change (LULCC) on the quality of freshwater systems are likely to be significant (IPCC, 2021). However, policy discussions and scientific studies have seldom addressed the important linkages between water quality, climate, and land use changes (IPCC, 2019; UNEP, 2016). Both LULCC and climate change affect key components of the water cycle such as runoff, soil moisture, evapotranspiration, ground water, and stream flow (Liu, et al., 2017; Mango et al., 2011). These changes in the hydrological components impact important sectors of the economy such as agriculture, energy, health, and tourism, among others (World Bank, 2020). Since the 1990's water pollution has worsened in many of the rivers and lakes in Latin America, Asia, and Africa (UNEP, 2016) due to abstraction, increased chemicals, sediments, and nutrient materials with serious implications on the ecosystems and livelihoods of many people (Kamran et al., 2017). Traditionally, the major culprits of water pollution due to chemicals, nutrients, and sediment were agriculture, industry, and urban activities (Torma et al., 2019; Mellander et al., 2018). However, recent studies point out that climate change also triggers and amplifies surface water pollution through extreme events such as floods and droughts (Rodrigues et al., 2019; Mellander et al., 2018).

Perhaps, one of the greatest challenges facing water resources management in the 21st century is how to account for the impact of climate and LULCC on water resources (Molina-Navarro et al., 2018; Shrestha et al., 2018; and Trang et al., 2017). Moreover, there exist a divide on whether it is climate or land use change which has a stronger signature on controlling water related processes and nutrients pathways. Some scholars have reported that at the local scale, the effects of LULCC on hydrological processes are more pronounced than the effects of climate change (Khoi et al., 2019; Gallo et al., 2015). But there are also those whose findings seem to suggest that the effects of LULCC are often contradictory and inconsistent due to the interaction between LULCC and climate change (Luo et al., 2020; Beck et al., 2013). Furthermore, some studies show that the combination of LULCC and climate change does not necessarily result in accelerating changes in water quality (Shrestha et al., 2017; Khoi & Suetsugi, 2014). The effects of both drivers may also offset each other (Zhang et al., 2016). On the other hand, scholars like

Giri et al., (2019), Ndulue & Mbajorgu (2018), and Trang et al., (2017) found out that the interaction between climate change and LULCC may lead to aggravated impact on water quality. Therefore, although climate and land use changes may interact and thus exacerbate or neutralize their individual and/or combined impact on water resources (Molina-Navarro et al., 2018), the consequences of the interactions on water quality are uncertain. Thus, studies on future water quality should account for the possible interactions between the impacts of climate and land use changes (Khoi et al., 2019, Serpa et al., 2017).

Multitudes of studies have investigated the individual and/or combined impact of climate and land use land cover change on water quality in different catchments under different climatic conditions around the world. For example, Khoi et al., (2019) reported a reduction in the wet-season and annual stream flow, and sediment and nutrient loads in the LA Buong River Basin in Southern Vietnam. The study also found that streamflow, sediment, and nutrient loads were more sensitive to LULCC than climate change. In the 3S River Basin in Vietnam, Trang et al., (2017) projected that discharge and nutrient loadings will increase and decrease in wet and dry seasons respectively and the basin is expected to contribute the highest nutrient loading in future. The study also reported that combined impact of climate and land use land cover changes will increase discharge through the century, while the nutrient yield of the basin will increase only in the near future. According to Molina-Navarro et al. (2018), changes in land use land cover alone showed an impact on NO_3^- loss due to change in fertilizer use while projected increase in discharge, organic nutrients, and PO_4^- loads were reported under high emissions in the Odense Fjord catchment (Denmark). The study also reported that both land use and climate changes will interact and jointly impact nitrate loads. In a similar study in the Songkhram River basin in Thailand, Shrestha et al., (2018) found out that future climate change will lead to a 24 % decrease in stream flow and 15.25 % decrease in nitrate-nitrogen loading under RCP 4.5 and 8.5 scenarios, respectively. Future land use land cover change was reported to contribute to a 6.35 % increase in stream flow and an 11.60 % decrease in nitrate-nitrogen loading under economic and conservation scenarios respectively, whereas climate and land use land cover change were seen to play against each other, creating a net effect of decreased future stream flow (16 % on average), and a decreased nitrate nitrogen loading (24.50 % on average), respectively. On the other hand, Ndulue & Mbajorgu (2018), projected a decrease in stream flow by 10.3 %, 26.2 %, 11.8 % and 26.72 % for urbanization and climate data in the 2020-2030 period, urbanization and

climate data in the 2040-2050, conversion of forests to agricultural lands in 2020-2030, and conversion of forests to agricultural lands in 2040-2050, respectively relative to the baseline (2005-2014) in the Upper Ebonyi river watershed, South East Nigeria. Serpa et al., (2017) meanwhile reported that climate change led to a decline in annual total nitrogen (TN) and total phosphorus (TP) exports while land use change resulted in an increase in stream flow, but variations were observed in water quality according to the scenarios. The study also found out that a combination of climate and land use land cover change scenarios revealed additive impacts on stream flow, TN, and TP.

According to literature, future climate and land use land cover changes will impact water quality at varying magnitudes and in different ways depending on: the location, current and future stock of water, and climate and LULCC scenarios, among others. Thus, more localized studies on the topic are required to extract context specific information and knowledge that can directly benefit policy and practice. In Uganda for instance, MWE (2015a) reported that the annual costs of inaction against climate change could be in the range of US\$3.2 to 5.9 billion within a decade, with the biggest impacts being on water, followed by energy, agriculture, and infrastructure and that from 2010 to 2050, the costs of inaction are estimated at between US\$273 to 437 billion. According to World Bank (2020), the past annual economic losses from droughts have been up to \$237 million. However, the cost of unmet water demand by 2050 could reach \$5.5 billion, with the largest losses expected in the Lake Victoria, Albert Nile, and Lake Kyoga basin whose water tower is the Mt. Elgon region.

The impact of climate change on ecosystem and society will be more pronounced in high-elevation mountain ranges, which are warming faster than adjacent lowlands (World Bank 2008). The pace of climate zone shifts will also be higher in such regions than in lowlands (Kohler & Maselli, 2009). In fact, many mountain regions of the world have become increasingly prone to destructive natural processes including earthquakes, volcanic eruptions, dam bursts, glacial lake outbursts, as well as landslides (Kohler & Maselli, 2009). In Mt. Elgon region for example, floods and series of shallow and deep landslides during heavy and sustained rainfall events (Mugagga et al., 2012) have claimed many lives and destroyed properties worth millions of dollar in the last three decades (World Bank, 2008). The situation is further worsened by the considerable loss of woodlands and forest cover due to deforestation and cultivation, particularly

on steep concave slopes of Mt. Elgon (Mugagga et al., 2012). The risk of landslide, flood, soil erosion, and water quality degradation in Mt. Elgon region is expected to increase in future, given the growing population, and the related expansion of settlements and infrastructure on the mountain (World Bank, 2008). Hence, there is a need for more research on climate and land use changes.

1.2 Statement of the problem

The Sironko catchment on the slopes of Mt. Elgon in Uganda lies within a fragile environment which is prone to climate related disasters such as droughts, floods, and landslides (UNDP, 2013; Knapen et al, 2006). The region is also one of the most densely populated, rapidly urbanizing rural parts of Uganda (Nakileza et al., 2017; UBOS, 2016). Population pressure is driving rapid land use changes in the region and all the available lands are intensively cultivated including the steep slopes and river banks (Mugagga et al, 2015; Mugagga et al., 2012). As a result, there are serious problems of sedimentation, river siltation downstream, and water quality degradation in most of the rivers of Mt. Elgon (Turyahabwe et al, 2020). This could be negatively impacting stream discharge and water quality with serious consequences on the ecosystems and livelihoods downstream. Yet, the catchment is one of the top suppliers of water to greater Kyoga Water Management Zone in Uganda. Given that most of the rivers, streams, and swamps in the Mt. Elgon are recharged and sustained by rainfall (World Bank, 2008), surface water sources are the most common fresh water supply to the communities. However, future provision of clean water in the region is projected to get worse amidst increasing demand and the amount of clean fresh water that is expected to reduce as a result of contamination from unprotected water catchments and poor sanitation especially in situation of increased rainfall intensity (World Bank, 2008). In low-lying parts of the ecosystem, fresh water availability is feared to be compromised by increased temperatures which can increase biodegradation and compound water quality problems (World Bank, 2008). The situation could even be exacerbated by the interactions between future climate and land use change.

Given its importance, the impacts of future climate and land use land cover changes on water quality in Mt. Elgon should be understood for sustainable management of the water resources. In spite of the above, quantitative data on the impacts of climate and land use land cover changes on

water quality in Sironko catchment are still inadequate. Quantitative studies are crucial to manage the expected increased risk of landslide, flood, soil erosion, and water quality degradation in Mt. Elgon region, given the growing population and the related expansion of settlements and infrastructure on the mountain (World Bank, 2008). Thus, there is urgent need to generate quantitative data on the impacts of climate and land use land cover changes on water quality in Sironko catchment to support adaptive management of the water resources in the catchment and the region.

1.3 Objectives

1.3.1 General objective

The general objective of this study was to contribute to improved understanding of the impacts of climate and land use land cover changes on water quality in tropical mountain environments, based on a case study of the Sironko catchment, on the slopes of Mt. Elgon, Uganda.

1.3.2 Specific Objectives

1. To synthesis the knowledge and trajectories of land use, land cover change at macro level in Uganda
2. To assess the dynamics of land use land cover change in Sironko catchment from historical to future conditions on a medium timescale
3. To assess the trends and magnitude of climate variability and change on a medium timescale in Sironko catchment
4. To assess the impact of climate and land use land cover changes on selected water quality properties in Sironko catchment

1.3.3 Hypothesis

- i. Forests will not significantly transition to agricultural land in Sironko catchment in the future scenarios.
- ii. September, October and November (SON) seasonal rainfall in Sironko catchment is not going to significantly change in the future scenarios
- iii. Nitrogen in Sironko catchment will significantly change in future compared to phosphorus
- iv. Land use land cover change in Sironko catchment is likely to have a significant effect on nitrogen as opposed to climate change in the future scenarios.
- v. Only climate change is likely to have a significant effect on stream flow in Sironko catchment in the future scenarios.

1.4 Justification of the study

Climate and land use land cover changes threaten the sustainability of humanity due to their impacts on ecosystems and livelihoods (IPCC, 2019). To support local context adaptive management and sustainable utilizations of environmental resources for improved livelihoods, more regional and local levels studies are needed on possible impacts of climate and land use land changes in the future (Zhou & Zhang, 2020). Hence, the justification and significance of these studies are as follows:

Quantitative data on the impacts of climate and land use land cover changes on water resources in Uganda are still limited. Yet, such data are vital for guiding strategic formulation of mitigation measures against possible future impacts of climate and land use land cover changes (Zhou & Zhang, 2020). This study is intended to bridge this knowledge gap at a catchment scale, and most importantly, in a fragile mountain environment (Sironko catchment on the slopes of Mt. Elgon). It is envisioned that the knowledge generated from this study will be used by the relevant stakeholders at different levels for making informed decisions regarding land and water resources planning and management in the region. For example, the utilization of the knowledge generated from this study by the relevant stakeholders can lead to improved water quality

management in the catchment and a reduction in the risk of water borne diseases. To have water of good quality in the catchment is also good for the ecosystem health, to reduce water treatment cost, and possibly lower water bills. To the scientific community, the research has generated publications on the topic in peer review journals and therefore has enriched the knowledge pool.

The study was also motivated by huge cost of inaction against future climate change in Uganda. MWE (2015a) reported that the cost of inaction against climate variability and future climate change could be between US\$3.2 billion and US\$5.9 billion within a decade and the figure would still rise over time even if the temperature, rainfall, and extreme events were to remain at current levels due to an increase in population (expected to grow by more than 2 % p.a. over the next 40 years) and GDP (expected to grow at around 7 to 8 % p.a. over the same period). The Uganda National Climate Change Policy (UNCCP) (MWE, 2015b) whose goal is “to ensure a harmonized and coordinated approach towards a climate resilient and low carbon development path for sustainable development in Uganda” is intended to mobilize national actions to adapt and mitigate such projected cost of climate change impacts. This study conducted on the impacts of climate and land use land cover changes at a catchment/local scale provides an avenue for the integration of local context issues into such important national policies.

The study also aligns with the Government of Uganda (GoU) long term National Development Plan (NDP) “Vision 2040” (GoU, 2007) whose aim is “to transform the country from a peasant and low-income economy to a competitive, upper-middle income economy by 2040”. Vision 2040 has a strong component of commercialization/mechanization of agriculture with increased inputs of chemical fertilizers and other agrochemicals (MFP&E, 2012) which may have serious consequences on land use land cover change and water quality in the country. Moreover, the medium-term National Development Plan (NDP III) 2020/2021-2024/2025 envisions the utilization of the water resources in the country as a key catalyst to the accelerated achievement of the Vision 2040 (NPA, 2020). The timing and the content of this study can therefore be very supportive to the implementation of the Vision 2040 and the NDP III, especially on issues relating to land and water resource planning and management in the country.

On a global scale, the study is in line with the United Nations’ (UN) Sustainable Development Goals 2015, goal No. 6 which calls for provision of clean water and sanitation for all and goal No. 15 which calls for protection, restoration, and sustainable use of resources on land.

1.5 Scope of the study

The study combined geospatial and modeling techniques to determining the impacts of climate and land use land cover changes on water quality. Broadly speaking the research was implemented in the grater Kyoga Water Management Zone (KWMZ). Specifically, the study boundary was restricted to the delineated Sironko catchment on the slopes of Mt. Elgon region in Eastern Uganda. Catchment boundary as opposed to administrative boundary was adopted based on hydrological principal and line with the concept of Integrated Water Resources Management (IWRM). Time series data were used with the smallest temporal unit being a day.

1.6 Conceptual framework

The conceptualization of the impacts of climate and land use land cover changes on water quality can range from fine to broad, static to dynamic and simple to complex scales. In spatial terms, that means working anywhere between micro-catchment to catchment/landscape scales. The temporal component looks at working from historical, current, and future. At organizational level, researchers have mostly aligned their studies to climate change, land use land cover change, and water resources in isolations. But more meanings are derived when these are expanded to address climate change, land use land cover change, and water quality holistically and at a catchment/landscape scale. More meaning can also be derived by understanding the past, current, and future impacts of climate and land use land cover changes on water quality (IPCC, 2021). Contextually, to look at broader scale complex things like climate and land use land cover changes, it requires stepping up to some of the more challenging aspects of research which are better understood through modeling approaches.

Hydrologists have long known that what goes on up on the land affects what happens in the water (Tempels & Hartmann, 2014). In particular, things we do up on the watershed can change the water quantity and quality. Climate change also greatly affected human society because things that happen in the watershed can work synergistically to change temperature, rainfall patterns, and in stream environment (World Bank, 2008). Changes in air temperature and rainfall for example, lead to changes stream flow.

Water quality (sediment/TSS, TN, and TP) are functions of flow, and at catchment level, both water quality and flow are influenced by a number of variables including land use and land cover

types; climate parameters, especially rainfall and temperature; soil types; and topography Figure 1.1. These variables interact with catchment elements such as fire, population, and market drivers and collectively influence runoff, infiltration, evapotranspiration, river flow, and hence water quality. In the same vein, projected climate and land use land cover changes are stressors of future water quality in the catchment. Climate change triggers and amplifies water pollution and both climate change and water pollution affect catchment management practices. On the same note, policy adaptation for best management practices not only improves the process interactions, control runoff, infiltration, river flow, and enhance water quality but also impacts positively on the land use and land cover types and climate. Therefore, proper planning, management, and supportive policies are required to mitigate future impacts of climate and land use land cover changes on water resources in the catchment.

Most parts of Sironko catchment are in a mountainous environment which means the main source of water input into the catchment is rainfall. Therefore, variation in rainfall has a direct effect on its discharge and hence water quality (sediment/TSS, TN, and TP). For example, flood events normally transport contaminants such as chemicals, heavy metals or other hazardous substances, either from landfills or from chemicals already in the environment like pesticides into water bodies, and hence compromising water quality (Torma et al., 2019; Mellander et al., 2018). Flood events can also cause landslides in a mountainous area (a common disaster in Sironko catchment) and drive a massive amount of sediments and debris into surface water (Fong et al., 2020). Higher water temperatures on the other hand, lower dissolved oxygen content (Jarvie et al., 2020) and can negatively impact fisheries and recreation activities. LULCC may either have a positive or a negative impact on water quality. For example, the conversion of a catchment dominated by bare land to a forested catchment results in high infiltration, low surface runoff, and trapping/delayed transportation of pollutants to surface water systems, hence giving time for biological clean up and improved water quality. Soil characteristics on the other hand affect water quality through its influence on catchment hydrological processes such as infiltration and surface runoff. Loosely packed soils with high infiltration rate and low moisture storage capacity are prone to erosion which ends up in river networks. The catchment topography meanwhile influences the process of surface runoff and water infiltration into the soil and aquifers. Catchments with open steep slopes (like the Sironko catchment) cause high surface

runoff which amplifies the transportation of pollutants to surface water systems compared to catchments with either flat or gentle slopes.

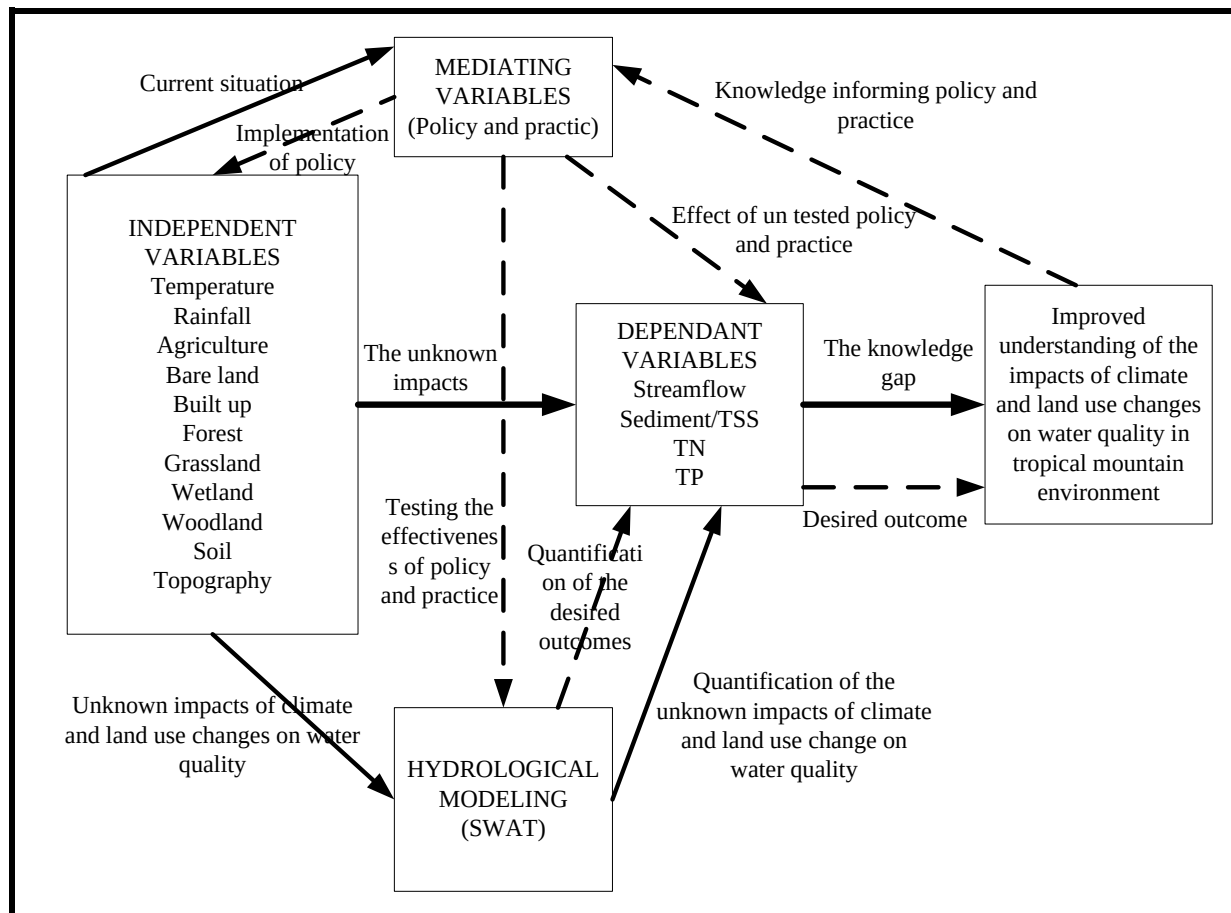


Figure 1.1 The conceptual framework for the impacts of climate and land use change on water quality

1.7 Organization of the thesis

This thesis consists of seven chapters as highlighted below:

- i. Chapter 1. The introduction, the statement of the problem, general and specific objectives, hypothesis, justification, scope, the theoretical framework, the conceptual framework, and the thesis layout.
- ii. Chapter 2. Literature on LULCC; historical and future climate change; impacts of LULCC, impacts of climate change; impacts of climate and land use land cover changes

on water quality, available models for assessing the impacts of climate and land use land cover changes on water quality, and the deductions from the reviewed literature.

- iii. Chapter 3. The general methodology (the map of the study area, climate, soil, land use, and the water resources; the philosophical foundation of the research; and the research approach (geospatial techniques, modeling, and activities implemented (pre, during, and post filed)).
- iv. Chapter 4. Systematic review and meta-analysis of LULCC on national, regional, and local scales in Uganda from 1998-2018.
- v. Chapter 5. The introduction, methods, findings, limitations, conclusion, and recommendation regarding the historical and future dynamics of land use land cover change and transitions on a medium timescale in Sironko catchment
- vi. Chapter 6. The introduction, methods, findings, limitations, conclusion, and recommendation pertaining to the trends and magnitude of climate variation and change on a medium timescale in Sironko catchment.
- vii. Chapter 7. The introduction, methods, findings, limitations, conclusion, and recommendation with respect to the impact of climate and land use land cover changes on the magnitude of selected water quality properties in Sironko catchment.
- viii. Chapter 8. Synthesis of key findings, conclusions, and recommendations.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of background literature related to the general and specific objectives of this study. It is presented in eight major areas beginning with historical and the current to near future land use and land cover dynamics; historical, current, and near future changes in climate; impacts of LULCC on water quality; impacts of climate change on water quality; the impacts of climate and land use land cover changes on water quality; impacts of LULCC in response to different drivers in Uganda; models selection for evaluating the impacts of climate and land use land cover changes on water quality; and a summary of the debate in literature on the impacts of climate and land use changes on water quality.

2.2 Dynamics of land use land cover between 1986-2016 and 2016-2040

Land is the main factor of production and LULCC is a necessary evil that humanity has to deal and live with. Extensive literature suggests that the planet Earth is undergoing unprecedented LULCC with diverse proportions and directions (Winkler et al., 2019; UNCCD, 2017). The changes in land use land cover are being driven by population growth, changing consumption patterns, and climate change (Chaturvedi et al., 2021). LULCC is increasing the pressure on natural systems and the ecosystem services they provide (Yirsaw et al., 2017; Zhang et al., 2017; Byrd et al., 2015). By 2015, human footprints such as urbanization, industrialization, and agriculture had claimed three-quarters of the total global land area leaving only 28 % of the global land area natural, of which 12 % is unusable to mankind (IPCC, 2019). According to Winkler et al., (2019), LULCC has affected almost a third (32 %) of the global land area in just six decades (1960-2019) and, thus, is around four times greater in extent than previously estimated from long-term land use land cover change assessments. Moreover, LULCCs are reportedly, more pronounced in developing countries where it is posing serious challenges to the sustainability of water resources management (Jazouli et al., 2019; Kleemann et al., 2017). Therefore, studies that quantify land use land cover dynamics are critical in tackling global societal challenges such as food and water security, climate change, and biodiversity loss.

In Uganda, UBOS, (2019) reported that built up areas increased from about 365 km² in 2005 to 670 km² in 2010 and to 1360 km² in 2015. Agricultural lands on the other hand, increased from

84,695 km² in 1990 to 95,211 km² in 2000 then to 100,000 km² in 2005-2010, and finally to 105,317 km² in 2015. Forests meanwhile, decreased in area from 49,334 km² in 1990 to 36,655 km² in 2005, and finally to 19,535 km² in 2015 while, wetlands change has been case specific with local studies reporting a mixed of increasing and decreasing trends. According to Ministry of Water and Environment (MWE 2015a), Uganda lost on average 122,000 ha/year of forest between 1990 and 2015, in favour of agricultural area expansion. Similarly, national area of wetlands declined by 30 % between 1994 and 2008, and slightly increased by 0.03 % between 2008 and 2014 (MWE, 2016). The numbers of urban centres increased from 67 in 1991 to 259 in 2014, while urban population increased from 0.6 million people in 1969 to 6.4 million people in 2014 (UBOS, 2016). The implications of the above are that the interaction of population growth and other drivers of LULCC are favouring agricultural lands and built-up areas expansion at the expense of forests, woodlands, wetlands with negative impacts on water quality.

A detailed review of LULCC in Uganda for the period (1998-2018) is found in (Luwa et al., 2020). The review clearly indicated that population pressure is the main driver of LULCC changes in different parts of the country (Luwa et al., 2020; UBOS, 2016). Uganda has a young and rapidly growing population (growth rate of above 3.03 % per annum). The total population was 34 million in 2014 and is projected to reach 80 million by 2040 (UBOS, 2016). However, environmental resources such as forest, wetlands, water, and grassland provided direct sources of livelihoods to over 80% of the population (UBOS, 2016). Given what is in literature, future pattern of LULCC in Uganda is uncertain hence, a need for more localised LULCC studies in the country to prepare for the future.

2.3 Historical (1980-2009) and current to near future (2011-2040) climate

Human influence has caused global warming at a rate that is unprecedented since the last two hundred years (IPCC, 2021). Climate change is manifested in three dimensions, 1) global average temperature rise, 2) changes in global rainfall patterns, and 3) rising sea levels (Oo et al., 2019). The variability in climate at local scales such as catchments or small basins affects agricultural production, food and water security, and the health of ecosystems (IPCC, 2019). Catchment scale knowledge of climate variability is vital for adaptive management of land and water resources in a changing environment (Langat et al., 2017).

In Uganda, evidence of the variability in rainfall and temperature at different spatiotemporal scales is inconclusive and gives mixed results (Mukasa et al., 2020; Mwaura & Okoboi, 2014; Diem et al., 2014). For example, the study by Mwaura & Okoboi, (2014) which covered the whole of Uganda reported insignificant variations in rainfall and temperature between 1981 and 2008. In the study by (Diem et al., 2014), a significant decrease in seasonal rainfall in western and central regions of Uganda was reported during 1983–2012. Similarly, (Mukasa et al., 2020) found that average annual rainfall and March, April, and May (MAM); January, December, and February (JDF) seasons rainfall in Kasali sub-county in Western Uganda decreased significantly between 1987 and 2017. Average maximum, minimum, annual, and seasonal temperature meanwhile increased significantly. On the other hand, Mubialiwo et al. (2020) and Nsubuga et al. (2014) reported significant increase in annual and MAM seasonal rainfall in the Mpologoma catchment in Eastern Uganda for the period 1948–2016 and in the Albert-Victoria water catchment area in Uganda for the period 1943–1977, respectively.

Concerning the future climate, Najjuma et al., (2021) characterized the historical and future drought in two coffee growing regions of Uganda. The study reported the highest drought frequencies of 16.7 % and 20 % in Bukomansimbi and Mubende respectively between 2001 and 2010. The historical period also recorded the highest drought records, magnitudes, and intensity with the pinnacle of the drought events occurring between 2005 and 2007. Future projection pointed the highest drought frequencies in the decades 2010-2030 and 2042-2050 where RCP 4.5 projected 11.9 % increase in Bukomansimbi and 15.6 % in Mubende while RCP 8.5 projected 9.2 % and 9.1 % frequencies in Bukomansimbi and Mubende, respectively. The conclusion of the study however, contradicted the reported findings where it was stated that drought will decrease in the future. Such contradiction opens up more room to replicating such study in order to reaffirm or dismiss the findings.

Nimusiima et al, (2019) characterized the past and future extreme rainfall over eastern Uganda between 1981-2010 (baseline) and 2021-2050 as future period. Decreasing trend of rainfall indices were reported for the historical period while projected trends were positives for all the indices except for daily intensity which was negatively projected under RCP 4.5. Shifts in the intensity values were significant with extremes also projected to increase in the future. However, in the context of this study such very interesting findings are considered limited in scope. It is

therefore important to build on what Nimusiima et al., (2019) reported and expand the scope to investigate the impacts of the projected climate change on water resources especially in a fragile catchment like the Sironko catchment.

The study of Egeru et al., (2019), analyzed the 1980-2009 and future rainfall and temperature over the Karamoja region of Uganda under RCP 4.5 and RCP 8.5. Significant increase in historical minimum temperature was reported between 2000-2008 while projected climate trends varied depending on the scenarios but with general increase in minimum temperature of between 1.8 °C (RCP 4.5) in the 2010-2039 period being reported while rainfall total amount will decrease. Again, the findings reported in Egeru et al., (2019) are open and the scope can be refocused from region to catchment and also to determine the impacts of the reported future climate on water resources in the region or elsewhere in Uganda, The current study used catchment rather than boundary districts to assess the impacts of climate and land use change on water quality.

2.4 Impact of land use land cover change on water quality

LULCC is a major stressor of water quality and it is a critical issue on the global environmental change agenda owing to its consequences on ecosystems and livelihoods (IPCC, 2019). Changes in land use land cover coupled with the impacts of climate change alter river flow (volume, timing and frequency) through the alternation of overland flow and infiltration, ground water recharge, flow velocity, and sediment detachment and transportation (Chaturvedi et al., 2021; Mango et al., 2011). Such processes amplify non-point sources pollution of surface water systems resulting from pollutants such as Nitrogen (N), Phosphorus (P), and sediment (Zhang et al., 2013). Non-point sources pollutions are difficult to manage due to their complex and diffuse nature and also because of how they interact with the hydrologic cycle and landscape patterns (Sliva & Williams, 2001). In tropical maintain environments, the relationship between land use land cover and water quantity is even more complex due to the interplay of climate change (Peters et al., 2019; Musau et al., (2015) and hence, the reason for more research in those areas.

Although recent studies provide compelling evidence in literature on the impacts of LULCC on water quality around the globe, there exist divergent views on the contributions of different land use land cover types in controlling water related processes and pollutants pathways. Scholars like

Paule-mercado et al., (2018) found that land development (conversion of vegetation to bare land and urbanization) were the major stressors of stream water quality. On the other hand, Tuomela et al., (2019) reported that pollution loads and sediment sources were highly fragmented and variable in urban catchment hence, it was impossible to single out the specific land use land cover type with the strongest signature on water pollution. Furthermore, Salim et al., (2019) found that erosion and settlement (domestic wastewater) are the primary source of water pollution. The study of Kroese et al., (2020) in the highlands of Kenya, found that agricultural land is the main source of sediments and nutrients loads into stream water followed by forest conversion.

A few of the studies have been highlighted below to further deepen the debate on the roles of different land use and land cover types on water quality. For instance, Misganaw & Aramde, (2019) focused on the effect of land use change on stream flow and sediment yield in the Gojeb Watershed, Omo-Gibe basin of Ethiopia over the period 1989, 2000, and 2013. The study reported that during period 1989, 2000, and 2013, agricultural lands increased by 14.97 % at the expense of forests and the change resulted in an increase in stream flow and sediment yields of 8.6 m³/s and 41.07 ton/km² respectively. In a similar study, Azanga et al., (2016) characterized the trend in LULCC and examined the change in sediment and nutrients hotspot areas in the Kalimabenge micro-catchment of Lake Tanganyika basin from 1973 to 2010. It was reported that sources of sediment, runoff and phosphorus in the micro-catchment first decreased in the 1986 and increased in 2010 corresponding to grasslands decline, gradual increase in forests, and fourfold increase in cultivated lands respectively. In the upper reaches of the Umngeni catchment in south Africa meanwhile, Namugize et al., (2018) found that cultivated, urban, and degraded areas increased by 6 %, 4.5 %, and 3 % respectively conceding with a decrease in natural vegetation by 17 % in the period 1994-2011 for the years 1994, 2000, 2008, and 2011. Furthermore, variability in concentration of water quality parameter and overall decline in water quality was also reported with water supply reservoirs in the catchment found to retain over 20% of the nutrients and over 55 % of the E. coli entering the reservoirs. The study of Uwimana et al., (2017), in the Migina catchment, south Rwanda showed that seasonal trends in water quality were associated with high flow and farming activities where TSS increased 2-8 times with high flow while electrical conductivity, DO, and pH reduced when discharge increased between 2009 and 2013. The pattern was however, not clear for TP and TN but it was noticeable that reaches

dominated by rice and vegetable farming (downstream) showed high concentration of TSS. TP and TN concentrations were particularly higher during dry season and early rainy season when farmers apply fertilizer at the start of the planting season.

On the slopes of Mt. Elgon, Turyahabwe et al., (2020) investigated the influence of land use and land cover on nutrients and physiochemical water quality in river Sironko catchment. Land use size was found to have a significant negative and positive correlation with TDS ($p = 0.0135$) and DO ($p = 0.0056$) respectively in the middle reach. On the lower reach, land use land cover size had a significant correlation with nutrients at ($p = 0.0344-0.0015$). Similar study was conducted in Namatala wetlands in eastern Uganda between April 2015 and October 2016 by Namaalwa et al., (2020). Key results of the study showed significant differences in total nitrogen (TN), phosphorus (TP) and total suspended solids (TSS) among the streams and among the different sections of the wetland. Nutrients and TSS were highest within the moderate rice farming and partly intact papyrus (*Cyperus papyrus* L) vegetation and lowest in drainage channels and mixed agriculture. Sediment and nutrient retention in the downstream part of the wetland compensated for increased export caused by agricultural and urban land use in the middle and upper zones of the wetland, thus maintaining net nutrient retention of Namatala Wetland.

2.5 Impact of climate change on water quality

Climate change is a key element on the global sustainability agenda due to its impacts on ecosystems and livelihoods (Molina-Navarro et al., 2018; Shrestha et al., 2018; and Trang et al., 2017). In the context of adaption, research on current and future impact of climate change on fresh water availability (quantity and quality) underpins sustainability of food and water security, livelihoods, and ecosystem health (UNCCD, 2017). Climate change is manifested in form of heavy rainfall and floods, rising temperatures facilitated by increased concentrations of GHGs especially CO₂ in the atmosphere, causing global warming and leading to the melting of ice and glacier, and sea levels rise among others (IPCC, 2021). These climatic conditions directly or indirectly affect in negative ways, the quality of surface water sources.

For example, contaminants such as chemicals, heavy metals or other hazardous substances either from landfills or from chemicals already in the environment like pesticides and also overload storm and wastewater systems get transported into water bodies during flood events (Mishra et

al., 2021; Torma et al., 2019; Mellander et al., 2018). Nutrients enrichment of surface water due to fertilizer runoff can cause algae blooms that ultimately end up suffocating aquatic critters in addition to causing a stinky unpleasant smell and increasing water treatment cost. Warming water, which cannot hold as much of the dissolved oxygen that fish need to survive even worsen the problem of eutrophication as it hinders the ability of a water body to effectively self-purify through biodegradation (Jarvie et al., 2020). Higher water temperatures can also lead to flourishing microbial populations (Bougouffa et al. 2013), which can have a negative impact on human health. Going beyond the *in-situ* effects, these conditions could harm fisheries, recreation, and the livelihoods of fishing communities. Generally, higher temperatures and changes in water supply and quality could affect recreational use of lakes and rivers or productivity of freshwater fisheries (Sundblad et al., 2020). Extreme rainfall events can also cause landslides in a mountainous area and drive a massive amount of sediments and debris into surface water (Fong et al., 2020). The sedimentation leads to siltation of rivers downstream and may cause the alteration of habitat and sometimes death of fish and benthic micro-organisms (Ustaoglu & Islam, 2020). On the other hand, the fall in stream flow and, lake and reservoir levels after flood events have been linked with less dilution of the pollutants and hence exacerbating water pollution (Mishra et al., 2021). In coastal areas meanwhile, sea level rise may also affect freshwater quality by increasing the salinity of coastal rivers and bays and causing saltwater intrusion, and movement of saline water into fresh ground water resources (Roy & Datta, 2018). Persistent drought conditions on the other hand, lead to depletion of groundwater reserves and the residual water that remains in such environment is often of inferior quality (Rodrigues et al., 2019).

Moreover, climate and land use changes may interact and thus, exacerbate their individual and/or combined impacts on water quality (Molina-Navarro et al., 2018). However, the consequences of the interactions between climate and land use changes on water quality are uncertain in most catchments around the world. Thus, studies on future climate should account for the possible interactions between the impacts of climate and land use changes on water quality Khoi et al., (2019); Serpa et al., (2017).

2.6 The combined impact of climate and land use land cover changes on water quality

The impact of future climate and land use land cover changes on the quality of freshwater systems are likely to be significant. However, the important linkages between water quality, climate, and land use land cover changes have seldom been addressed in policy discussions and scientific studies (IPCC, 2021). In an effort to inform such important policy, researchers are now more interested in investigating the linkage between water quality, climate, and land use land cover changes. Some of the scholars who have investigated the individual and/or combined impacts of climate and land use land cover changes on water quantity and quality in different catchments under different climatic conditions around the world are here highlighted.

Giri et al., (2019) evaluated various components of the hydrological cycle including sediment transport for three scenarios one at a time for climate change alone, land use and land cover change alone, and climate and land use and land cover change combined in the Neshanic River Watershed in central New Jersey, USA. The SWAT model was used to simulate the impacts of climate and land use land cover changes on stream flow and sediment dynamics. Future climate in 2020 to 2045 was projected using 10 ensembles of GCMs for emission scenarios RCP 4.5 and RCP 8.5 respectively while future land in 2040 was developed using driving factors such as distance to residential, agricultural land, stream, to mention a few. Result indicates that changing climate will have larger effects on the hydrological cycle than intensification of urban land in the watershed. The climate change scenarios, either alone or in composite with land use land cover change, predicted higher stream flow (32 % and 36 % increase over baseline, respectively), overriding the effect of land use land cover change which predicts a decline of 5 % in stream flow. The increase in stream flow resulted in an increase in sediment loading, possibly due to an increase stream down cutting. The conversion of agricultural land to low density residential uses is predicted to decrease sediment load. Combined effect of conversion of erodible agricultural fields to suburban development appears to override the adverse effect of climate change, leading to a reduction in sediment load.

The study of Trang et al., (2017) on the other hand, evaluated the impact of climate and land use land cover changes on nutrient yield in the 3S river basin in southern Vietnam. SWAT was used for evaluation of climate and land use changes impact while future climate in 2030s, 2069, and

2090s were derived from ensembles of five GCMs under RCP 4.5 and RCP 8.5 emission scenarios respectively. Secondary DEM, soil, and land use map of the basin was obtained from the Mekong River Basin Commission while the climate of the basin was projected to become warmer and wetter under both RCPs with nutrients load predicted to increase in wet season and decrease in the dry season. Furthermore, it was found that both climate and land use land cover changes will lead to nutrient yield increase throughout the 21st Century.

Furthermore, Shrestha et al., (2017) employed SWAT to simulate the combined impacts of future climate and land use land cover changes on water yield and total nitrogen and total Phosphorus loads in the Onkaparinga catchment in southern Australia. Ensemble of six GCMs was downscaled to derive the future climate of the catchment under two emission scenarios RCP 4.5 and RCP 8.5 respectively. Climate models revealed high degree of uncertainty, varying seasonally in both flow and nutrient loads but decreasing trend. Average monthly TP and TN loads decreased up to 55 % and 56 % respectively and was dependent on flow magnitude. Future land use was found to slightly alter annual and seasonal water yield and nutrient loads while future climate significantly altered flow and nutrient loads under both RCP 4.5 and RCP 8.5 especially in the spring season. The combined impacts of climate and land use land cover changes however, indicated decreasing flow in the future but nutrient enrichment in the summer months mainly as a result of land use scenario.

In the Xitiaoxi watershed in southeastern China, Luo et al., (2020) assessed the isolated and coupled effects of future climate and land use land cover changes on stream flow and nutrient loads. The calibrated Hydrological Simulation Program “Fortran” model was applied under four RCPs and two land use land cover change scenarios. The study reported that climate change would induce seasonal shifts in nutrient loads and the effect of land use land cover change showed that nutrient loads were more sensitive than flow where Orthophosphate load increased by 2.8-154.7 % and flow increased by 7.2-15.1 % respectively. Coupled effects of climate and land use land cover changes suggested that flow and nutrient loads would be more affected by climate change than land use change. Climate and land use land cover changes may amplify or weaken each other effects on flow and nutrient loads and both should be considered in hydrological modeling when studying future impacts.

Khoi et al., (2019), meanwhile reported a reduction in the wet-season and annual stream flow, and sediment and nutrient loads in the LA Buong River Basin in Southern Vietnam. However, the study also found that stream flow, and sediment and nutrient loads increased under the effects of the land use change with stream flow, and sediment and nutrient loads being more sensitive to land use land cover change than climate change.

In the Odense Fjord catchment, Denmark, Molina-Navarro et al., (2018) reported that changes in land use land cover alone showed an impact on NO_3^- loss due to change in fertilization while projected increase in discharge, organic nutrients and PO_4^- loads were reported under high emission scenarios The study also reported that both land use land cover and climate changes will interact and jointly impact nitrate loads.

The study of Ndulue & Mbajiorgu, (2018) on the other hand, reported a decrease in stream flow by 10.3 %, 26.2 %, 11.8 % and 26.72 % for Scenarios 1, 2, 3, and 4 respectively relative to the Baseline (2005-2014). In the Upper Ebonyi river watershed, South East Nigeria. Serpa et al., (2017), meanwhile reported that climate change led to a decline in annual total Nitrogen (TN) and total phosphorus (TP) exports under both A1B and B1 emission scenarios while land use change resulted in an increase in stream flow, but variations were observed in water quality according to the scenarios. The study also found that a combination of climate and land use land cover changes scenarios revealed additive impacts on the exports of sediments TP and TN.

2.7 Models for assessing the impact of climate and land use land cover change on water quality

Model for a particular study is selected based on the objective, scope, temporal and spatial resolution of the model (Trambauer et al., 2013). Additional criteria may include; ease of access, input data requirements, cost, expertise, availability of model code, existing user community, flexibility to grid structure, possibility of calibration with suitable tools, data assimilation and availability of user manual (Kauffeldt et al., 2016). Many hydrological models for catchment scale studies do exist. For example, the Soil and Water Assessment Tool (SWAT); the Hydrologic Simulation Program-Fortran (HSPF), the Integrated Catchment Model (INCA), and SPA tally Referenced Regression on Watershed attributes (SPARROW), Universal Soil Loss Equation (USLE) and Variation, Water Erosion Predication Project (WEPP), However; MIKE

SHE, Hydrologiska Byrans Vattenavdelning model (HBV); and the Variable Infiltration Capacity model (VIC) among others. However, reviews on the application of the models have always reported that the Soil and Water Assessment Tool (SWAT) is the most popular of all.

SWAT is a physically based, semi-distributed hydrological model that predicts the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds of varying soils, land use and land cover, and management conditions over long periods of time (Neitsch et al., 2011). The model was developed for the United States Department of Agriculture (USDA)-Agricultural Research Services (ARS) for assessing the impact of human activities on water quantity and quality (Arnold et al., 1998). The model uses digital elevation model (DEM) to divide the catchment into sub-catchments that are further subdivided into Hydrological Response Units (HRUs) based on soil type, land use and land cover, and slope (Neitsch et al., 2011). HRUs are areas of the catchment which respond to rainfall events in the same way due to homogenous soil, land use and land cover, and slope characteristics. The HRUs form the basic unit of hydrological response in the SWAT model. Simulation of a catchment hydrology in the model is divided into land and routing phase. The land phase represents the amount of water and pollutants (sediment, nutrient and pesticides) entering the river channel while the routing phase defines the movement of water and pollutants through the river channels to the catchment outlet (Neitsch et al., 2011). The model simulates the hydrological cycle based on the water balance (Equation 2.1).

$$SW_t = SW_o + \sum_{t=1}^t (R_i - Q_i - ET_i - P_i - QR_i) \quad \text{Equation 2.1}$$

Where, SW_t is the final soil water content, SW_o is the initial soil water content of the day i , t is time in days, and R , Q , ET , P , and QR are the daily amounts of precipitation, surface runoff, evapotranspiration, percolation, and return flow respectively all measured in mm.

The model has been successfully applied in both small and large catchments all over the world because it is free <http://swat.tamu.edu/> efficient, flexible and continuous-time model that uses readily available data (Arnold et al., 1998; Neitsch et al., 2011). The model also has one of the largest and most active global online user support community. The model in addition uses the automatic SWAT-Calibration and Uncertainty Procedures (SWAT-CUP) for calibration outside

the SWAT software making the process easier. Therefore, SWAT model was used in this study to simulate the impacts of climate and land use changes on stream flow, sediments and nutrients loads in Sironko catchment.

2.8 Deductions from the literature reviewed

Based on the review of literature, this study noted that within the land use land cover scholars, there are divergent views on the roles of different land use land cover types in influencing and controlling water pollution and pathways. There are those who look at urbanisation as major threats to water quality but there are also those who view conversion of forests to other land use types as the major drivers of water quality pollution. On the other hand, there is also group who concur that agricultural lands and related processes are the major threat to water pollution while there is a section who say wetlands encroachment is the main driver of water pollution. Similarly, the debate on whether climate change or LULCC has stronger signatures on surface water pollution is more or less a question of “chicken and the egg”. It is practically difficult to say/tell which comes first and which leads to the other? This is because the effects of climate and land use changes on water quality vary depending on the location, available stock of freshwater, and on the land use land cover or climate scenarios under consideration (IPCC, 2021, 2019). Within the pool of (climate, land use land cover, and water resources) scholars, there are those whose findings are more aligned to LULCC while there are also those who found that climate matters most when it comes to water pollution. Similarly, there are those who debate in the middle with the view that both climate and LULCC have equal effects on water quality and their combined impacts may aggravate or cancel each other. Additionally, there is a group that remains undecided. The different approaches scholars have used also made it difficult to conclusively assess the impacts of climate and LULCC on water quality. However, literature suggest that the integration of GIS, remote sensing, and geospatial techniques in conjunction with application of physically based hydrological models (especially SWAT model) has greatly improved the understanding of the impacts of climate and LULCC on water in many catchments around the world. These divergent views and contradicting findings call for further investigations on the effects of climate and LULCC on water quality at catchment scales. Knowledge generated from such studies can help in estimating the effectiveness of land use management practices at especially in catchments of tropical mountains such as Sironko.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Study area

3.1.1 Location

The study was conducted in Sironko catchment located at an altitude range of 1043 to 4297 (m.a.s.l) on the slopes of Mt. Elgon (Figure 3.1). The catchment lies between latitude $1^{\circ}10'0''$ - $1^{\circ}40'0''$ N and longitude $34^{\circ}10'0''$ - $34^{\circ}50'20''$ E and, covers an area of 3927 km². According to Vedelda et al. (2016), the Mt. Elgon region has over the last three decades witnessed many environmental hazards (floods, droughts, mudslides, and landslides) which have negatively impacted water quality and the livelihoods of the local communities.

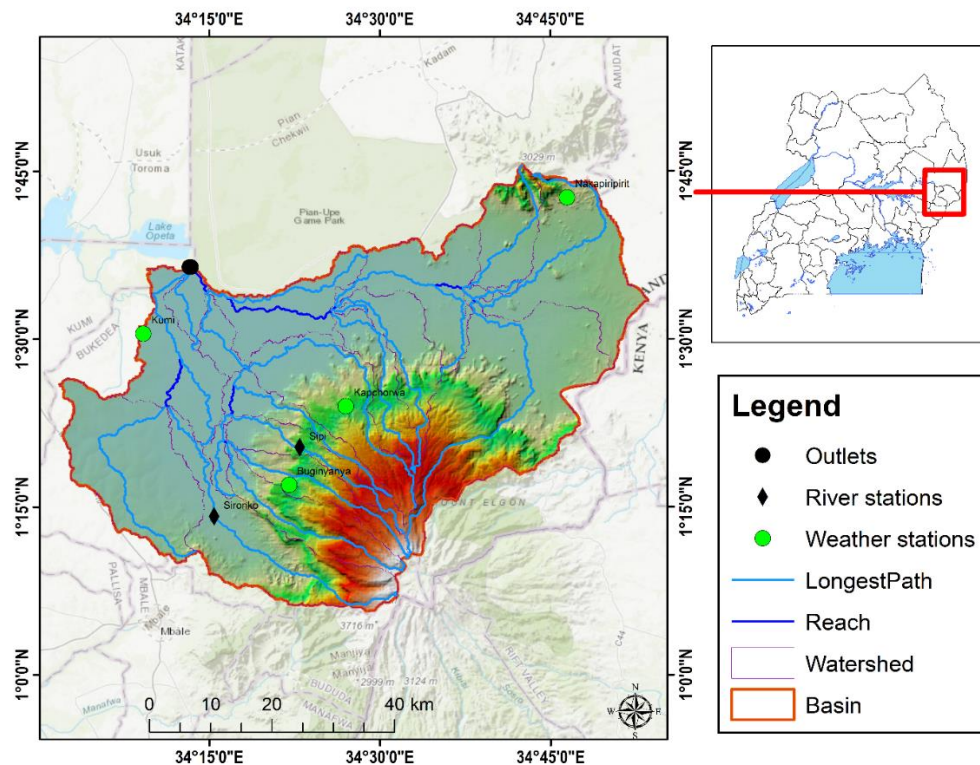


Figure 3.1: Location of Sironko catchment

3.1.2 Climate

The Sironko catchment experiences equatorial type of climate with clear distinctions between the wet and dry seasons. The rainfall characteristic of the catchment is weakly bimodal in nature.

The first rainfall season starts in March and spread over April, and May while the second rainfall season begins in August, September, and October although it spills over to November (Figure 3.2). The dry season extends from December to February while June to July though, not considered dry months, also receive relatively low rainfall.

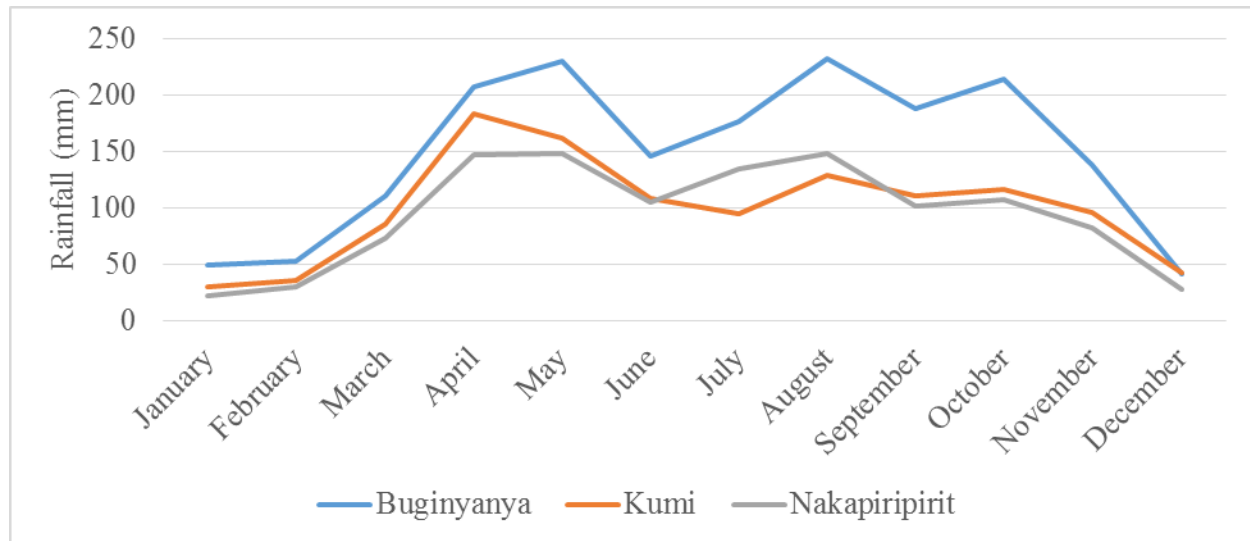


Figure 3.2: Monthly mean rainfall patterns for Buginyanya, Kumi, and Nakapiripirit stations for the period 1980-2009

Monthly mean temperature for the period 1980-2009 in Sironko catchment is presented in (Figure 3.3). The figure indicates that Kumi station is about 2 °C warmer than Buginyanya and Nakapiripirit stations respectively. On the other hand, Buginyanya is slightly warmer than Nakapiripirit station by about 0.5 °C from January to July. However, from August to December, Nakapiripirit gets slightly warmer than Buginyanya.

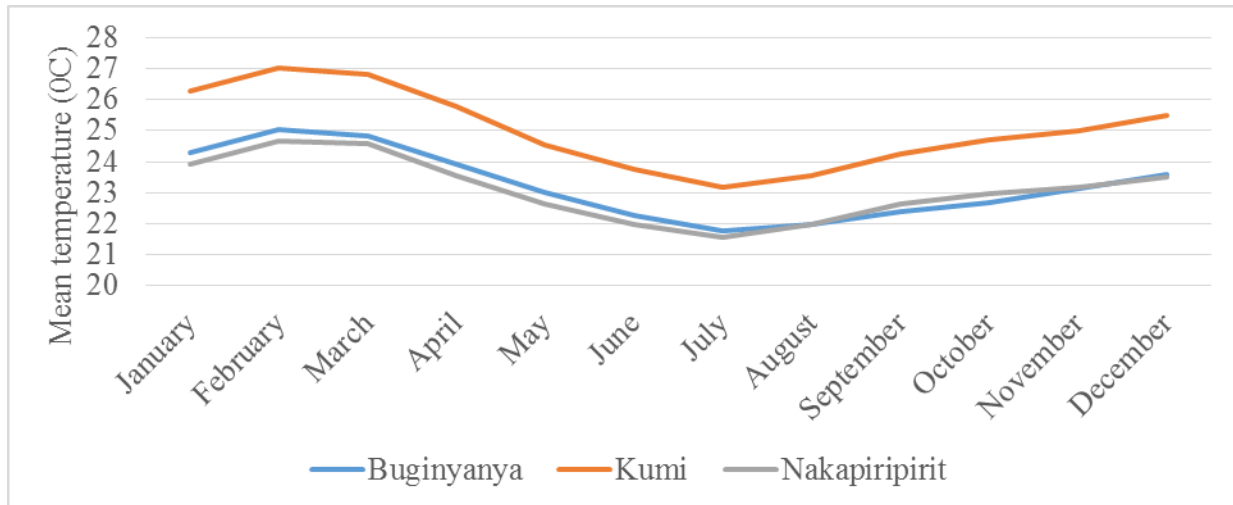


Figure 3.3: Monthly mean temperature in Sironko catchment from 1980-2009

3.1.3 Geology and soil

The soils of the study area were identified as inorganic clays of high plasticity. According to Mugagga et al, (2012), the soil of Mt. Elgon region is referred to as vertisols characterized by a clay content exceeding 41 %.

3.1.4 Land use and land cover

There are seven main land use and land cover types in Sironko catchment that is: agricultural lands; grassland, wetlands, forests, woodlands, built up areas, and bare lands. According to Buyinza & Mugagga (2010), all available land in Mt. Elgon region (the Sironko catchment inclusive) is intensively used for farming even on the steep slopes of the mountain. Generally, little soil conservation practices are carried out in the Mt. Elgon region (Mugagga and Buyinza, 2013). The most commonly grown crops in the region include banana, coffee, maize, and beans (Nakileza et al., 2017).

3.1.5 Water resources

River Sironko originates from the Mt. Elgon Forest complex and it flows northwards into a papyrus wetland before draining into Lake Opeta, Lake Kyoga, and finally into River Nile. Due to its mountainous nature, the Sironko catchment houses the Sipi falls which is one of the most popular tourist sites in eastern Uganda (Fodor & Messerli, 2013). The communities within the

catchment are highly dependent on the river water for domestic and urban water supply, livestock watering, small scale irrigation and fishing. The government has also planned a big water supply investment project in the catchment. However, Amoti et al. (2015), warned that abstractions due to the proposed project will reduce the flows in the target rivers and streams and may lead to serious consequences on ecosystems and livelihoods downstream.

3.2 The general methodology

3.2.1 Research approach

The approaches undertaken to achieve the specific objectives of this research were geospatial techniques and modeling. To avoid repetitions, the approaches were only highlighted in this section of the thesis while the detailed design, procedures, materials and methods used in answering each of the specific objectives have been dealt with under the respective chapters (4 to 7) of this thesis.

Geospatial techniques involved the use of Geographical Positioning System (GPS), Remote Sensing (RS) and Geographical Information Systems (GIS). A GPS receiver was used in geo-referencing the outlet and, points to validate image classification. Remotely sensed satellite images were obtained and used to map and classify the land use and land cover in the catchment while, GIS was used in the generation and digital extraction of relevant parameters, analysis and integration of various datasets to facilitate geospatial modeling of future land use and land cover.

Modeling techniques were used to address parts of objective 1 and 3 of this research. Future scenarios of land use were predicted using the Markov Chain process in the Terrest Land Change Modeler as detailed in chapter five. Climate scenarios were projected by downscaling 29 General Circulation Models (GCMs) based on the AgMIP delta method using R script (see chapter six for details). The impacts of climate and land use change on the magnitude of selected water quality parameters was determined by modeling using SWAT model (details in chapter seven).

Under objective 1, the years 1986, 2000, and 2016 were purposely selected giving fifteen years in between to capture any major changes that could have occurred in forest since it takes a long time to regenerate. Accordingly, the period 1986-2000 would reveal the dynamics and transition of land use land cover in the catchment during the time when there was insecurity and no rule of

law in most parts of the country. It is probable that the lack of rule of law could have negatively impacted environmental conservation efforts in the 1980-1990 and resulted in the observed spatiotemporal pattern of land use land cover dynamics in Sironko catchment (Cavanagh & Benjaminsen, 2014; Ditiro et al, 2008). Similarly, the period 2000-2016 represents the time when the National Resistance Movement (NRM) government restored peace and the rule of law dating back to the mid-1990s. The 1995 constitution of the Republic of Uganda gave birth to the National Environment Management Authority (NEMA) in 1999. NEMA is mandated by the constitution to oversee and ensure environmental conservation in the country. The deliberate policies could have been reflected in the observed spatiotemporal pattern of land use land cover dynamics in the study catchment (Cavanagh & Benjaminsen, 2014). The period 2016-2040 was chosen to depict the current to near future land use land cover dynamics and transitions in Sironko catchment.

Considering objective 2 part one, observed daily rainfall and temperature data (1981–2015) for Buginyanya and Kapchorwa weather stations from the Uganda National Meteorological Authority (UNMA) and daily river flow data for River Sipi (1998–2015) from the Ministry of Water and Environment (MWE) were used. Part one investigated fine-scale variability in climate and river flow in Sipi sub-catchment. It was restricted to Sipi sub-catchment due to data availability at that scale. However, the finding was integrated and discussed together with part two. Under part two, the periods 1980-2009 and 2025-2040 were selected to assess the trends and magnitudes of climate variability and change during baseline and medium timescale/future, respectively. Furthermore, the periods 1980-2009 and 2025-2040 were later used to model the impacts of climate and land use change on the magnitude of selected water quality parameters in Sironko catchment under chapter seven. The future was restricted to 2040 to avoid the uncertainty associated with long term projections. Three virtual weather stations Buginyanya, Kumi, and Nakapiripirit were selected to give a better coverage of the entire catchment. Moreover, this study used daily rainfall, temperature minimum and maximum, solar radiation, wind speed, and relative humidity from the Modern Era-Retrospective Analysis for Research and Applications (MERRA) provided by the Agricultural Model Inter-comparison and Improvement Project (AgMIP) for baseline 1980-2009 and future scenarios 2025-2040 climate to overcome the problem/lack of observational data as later explained in chapter six. The 2025-2040 climate of the catchment was downscaled from 29 GCMs as detailed in chapter six. The analysis was

restricted to two emission scenarios Representative Concentration Pathways (RPCs) RCP 4.5 and RCP 8.5 and for five climate regimes (Cool/wet, Hot/wet, Cool/dry, Hot/dry, and Middle) as justified in chapter six.

Under objective 3, only pH, EC, TDS, TSS, DO, BOD₅, COD, Total nitrogen (TN), total alkalinity, total hardness, Total phosphorus (TP), turbidity, and fecal coliforms were selected and monitored from January-December, 2018 as justified in chapter seven. The impacts of climate and land use land cover changes on the magnitude of selected water quality parameters in Sironko catchment were modeled using the Soil and Water Assessment Tool (SWAT). SWAT was selected as later justified in chapter six.

3.2.2 Activities implementations

The research involved the renaissance, the fieldwork, and post fieldwork activities implemented as summarized the methodological framework used in the study (Figure 3.4). The renaissance involved: 1) synthesis of the land use and land cover change status in Uganda. This was carried out through a systematic review and meta-analysis of 42 LULCC studies conducted in Uganda from 1998-2018 on national, regional, and local scales. Details of the methods used and key findings of the review can be found in chapter four based on (Luwa et al., 2020). 2) downloading of three sets of Landsat 30 m imagery 1986, 2000, and 2016 and the Digital Elevation Model (DEM) 30 m of eastern Uganda from Earth explorer. 3) downloading weather data (rainfall, temperature minimum and maximum, solar radiation, wind speed, and relative humidity) for the virtual weather stations Buginyanya, Kumi, and Nakapiripirit respectively.

The fieldwork activities involved the following: 1) outlet identification. 2) ground truth survey. 3) secondary data collection rainfall and temperature from UNMA and river flow from MWE, 4) assessing site-specific and seasonal variations in selected water quality parameters along a segment of river Sironko. This was achieved by collecting water samples once a month at seven monitoring sites from January to December 2018. Samples were analyzed at the National Water and Sewerage Corporation (NW&C) laboratory in Mbale following the standard methods for examinations of water and wastewater. More details and the key finding of this part of objective are found in chapter seven of this thesis.

The post filed activities carried out under objective two were: 1) delineation of study catchment, 2) extracting the images of the catchment, 3) preprocessing the images, 4) classification of the images, 5) accessing the accuracies of the classification, 6) detecting the changes and transitions of land use, 7) generation of transition potential sub models, 8) projecting the land use in 2040. To accomplish objective three, the following tasks were implemented: 1) UNMA and MWE data quality control. 2) analysis of UNMA and MWE data for variabilities and trends at sub-catchment. 3) extracting MERRA climate data for the virtual stations (Buginyanya, Kumi, and Nakapiripirit) from USGS website, 4) downscaling GCMs for application in Sironko catchment. 5) selection of the best performing models under Cool/wet; Cool/dry; Hot/wet; Hot/dry; and Middle climate regimes respectively. 6) analyzing the trends and magnitudes of variability and change in rainfall and temperatures in the medium timescale 2025-2040. Objective 4 was achieved by: 1) setting up SWAT model for Sironko catchment. 2) calibration and validation of the model for discharge and sediments. 3) determining the 1980-2009 and 2025-2040 impacts of climate and land use changes on streamflow, sediment, TN, and TP in Sironko catchment using the calibrated and validate SWAT model.

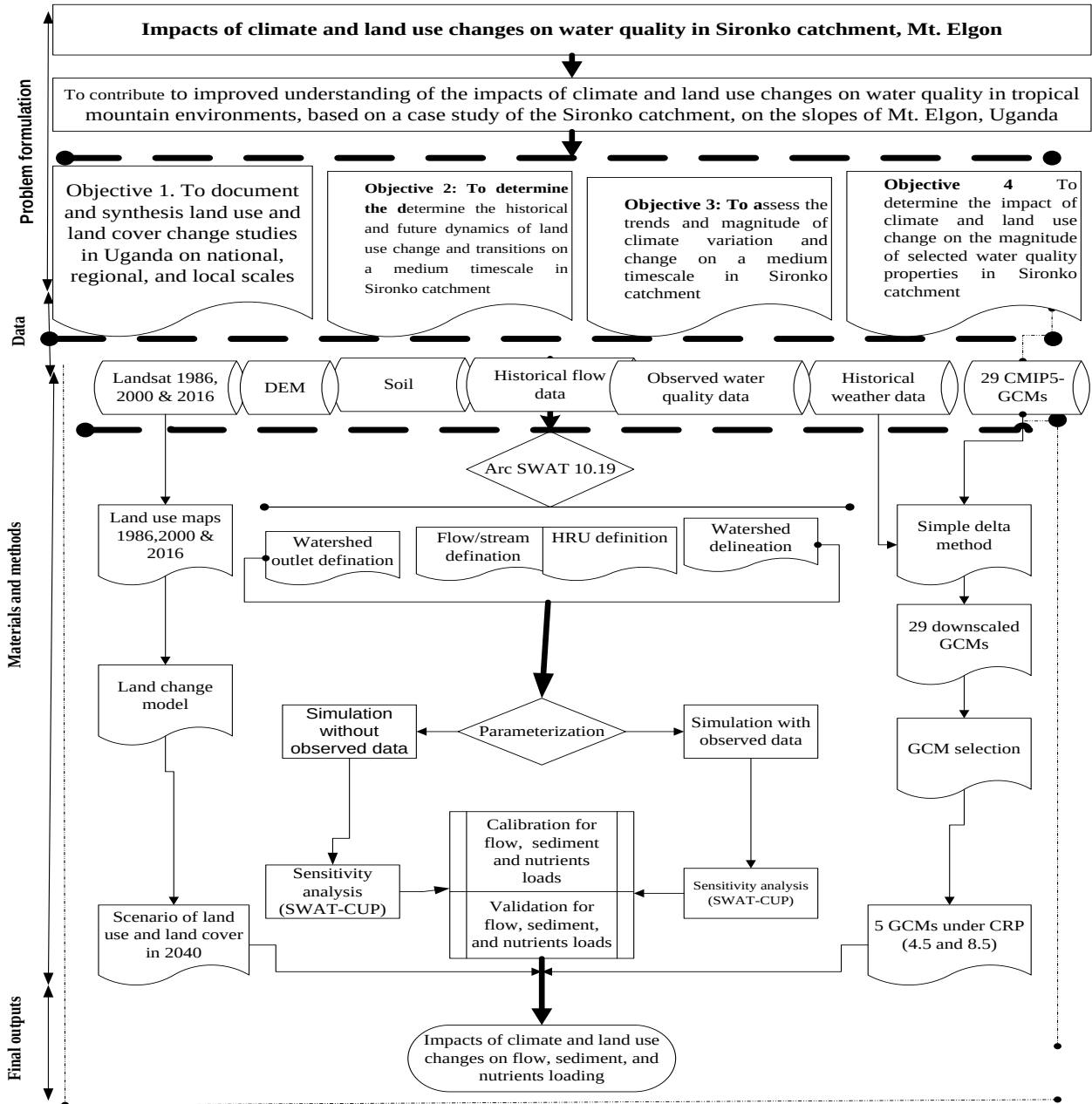


Figure 3.4: Methodological framework used in the study (self-constructed)

CHAPTER FOUR: KNOWLEDGE AND TRAJECTORIES OF LAND USE LAND COVER CHANGE AT MACRO LEVEL IN UGANDA

4.0 Abstract

Many case studies have often reported different and sometimes contradicting results on Land Use Land Cover Change (LULCC) in Uganda. It is likely that the heterogeneous geographical landscape and the socio-cultural diversity in Uganda have bigger roles to play in shaping the LULCC change dynamics. Thus, there could be unique patterns and drivers of land use/cover change in different regions of the country. Yet, documentation and synthesis of LULCC change studies in Uganda at national, regional, and local scales still remains limited. This study assessed the knowledge and trajectories of (LULCC) at macro level in Uganda. LULCC studies in Uganda from 1998 to 2018 were reviewed based on the framework of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. The aim was to document and synthesise the findings to shed light on the impacts and the drivers of LULCC at regional scales. Results indicate agriculture, forest, grassland, and woodland as the major land use and land cover types. Central Uganda is the most studied region (36 %), followed by western (33 %), eastern Uganda (24 %), and northern Uganda (7 %). District scale studies contributed 48 %, catchment (19 %), forest (17 %), national (10 %), and parks (7 %). Up to 93 % of the literature analysed LULCC based on Landsat 30m resolution and remote sensing. LULCC drivers in Uganda interact at different spatiotemporal scales. Population stands out of all the major drivers of LULCC. The impacts of LULCC are site specific and include reduction of: tree cover and species composition; water quality and quantity; and soil quality. Stakeholders at different levels need to integrate local context socioeconomic, cultural, and environmental settings in the design and implementing of policy relating to land resources management to ensure the sustainability of resources and livelihoods.

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4.1 Introduction

Land use land cover change (LULCC) can result from both intentional and non-intentional human activities or as a result of natural causes. However, human forces are now known to be altering the natural global landscape at unprecedented magnitudes and at different spatial-temporal scales (Turner et al., 2009). LULCC also induces changes in ecosystem goods and services which are vital for livelihoods (Maitima et al., 2009). In the 21st century, LULCC is a topic of global concern because of its effects on sustainable development and human wellbeing (Turner et al., 2009). In many developing countries, land degradation as a result of undesired LULCC has led to reduction in food production, and threatened livelihoods (Maitima et al., 2009).

Many studies on LULCC change have been conducted in Uganda at different spatial and temporal scales for different reasons. For example, Anaba et al. (2017) focused on the impacts of LULCC on water quality in the Murchison Bay of Lake Victoria. Wadembere & Kobugabe, (2017) investigated urbanisation and its effects in western Uganda. In northern Uganda Gorsevski, et al., (2012) assessed the effect of armed conflict on forest ecosystem while Nyeko, (2010) looked at land use change and water resources management in Aswa basin of northern Uganda. In eastern Uganda, Mugagga et al., (2015) were interested in land use change, carbon stocks, and climate variability in Mt. Elgon region while Mugagga et al. (2012) investigated LULCC and implications to landslides occurrences in Mt. Elgon, eastern Uganda. On the other hand Li et al., (2016), Zhou et al. (2017), Jagger & Kittner, (2017), and Majaliwa et al. (2018), LULCC at national scale. What emerges from literature is that LULCC is complex and driven by both natural and anthropogenic factors that interact in space and time.

Uganda is projected to attain a middle-income economy by 2040 on the background of a young and rapidly growing population (growth rate of above 3.03 % per annum). The total population was 34 million in 2014 and is projected to reach 80 million by 2040 (UBOS, 2014). But environmental resources such as forest, wetlands, water, grassland and others provide direct sources of livelihoods to over 80 % of the population (UBOS, 2014). Population pressure and other socio-economic and natural drivers are leading to unprecedented LULCC changes at different spatial and temporal scales in Uganda (UBOS, 2014). It is also important to note that

Uganda is so diverse in terms of the landscapes, sociocultural, and economic settings, which compound LULCC. Given the above background, government agencies and policy makers may need to invest in redesigning current land use policies and/or develop new approaches so that the policies meet specific local context with specific drivers, causes and impacts. To provide a basis to rethink the old and current approach to land resources management, this study systematically reviewed 42 LULCC studies conducted in Uganda from 1998-2018. The aim was to document and synthesise the findings to shed light on the impacts and the drivers of LULCC at regional scales. Such information is needed to provide decision support to stakeholders at different levels regarding land use planning and management.

4.2 Materials and methods

4.2.1 Description of study area

Uganda is a landlocked country in East Africa located in Southeast Africa between 1° N and 4° N latitude and 30° E and 35° E longitude. The country has a total surface area of about 241,500 km² of which land occupies 194,000 km² and the rest is open water and wetlands (UBOS, 2014). Uganda has equatorial type of climate with mean annual temperatures ranging from 16 °C to 30 °C (UBOS, 2014). Two rainy seasons are experienced in the central, western, and eastern regions from March to May and September to November. The northern region receives one long rainy season (April-October) in a year. Average annual amount of rainfall received in most parts of the country ranges between 750 mm and 2,100 mm (UBOS, 2014). Uganda's vegetation varies, with the south having tropical rain forest and savannah, while woodlands and semiarid vegetation dominate the other parts of the country. The country has one of the highest population growth rates (> 3 %) in the world and over 80 % of its 34,6 million people derived their livelihoods from services of agriculture (UBOS, 2014). The actual (1991-2014) and projected (2020-2030) population is highest in the central region, followed very closely by western, eastern regions and northern region respectively. However, northern region is the largest in area followed by central, western, and finally eastern Uganda as seen from (Table 4.1).

Table 4.1: Actual 1991-2014, projected 2020-2030 population, and area of Uganda by region

Regions	Census 1991	Census 2002	Census 2014	Projected 2020	Projected 2025	Projected 2030	Area in (Km²)
Central	4,843,594	6,575,425	9,575,425	11,562,900	13,608,500	15,836,200	61,403.20
Western	4,547,687	6,298,075	8,874,862	10,577,900	12,238,000	13,987,500	55,276.60
Eastern	4,128,469	6,204,915	9,042,422	10,836,500	12,503,100	14,137,400	39,478.80
Northern	3,151,955	5,148,882	7,188,139	8,606,300	9,967,700	11,449,300	85,391.70
National	16,671,705	24,227,297	34,634,650	41,583,600	48,317,300	55,410,400	241,500

Source: (UBOS, 2018)

4.2.2 Review framework

The current study focuses on review of LULCC studies within Uganda and it was restricted to only electronically available literature. The review was conducted within the framework of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Figure 4.1). PRISMA is an evidence-based minimum set of items for reporting systematic reviews and meta-analyses. It was developed for use in the medical field (Von Elm et al., 2007) but its applications have evolved to many fields, especially the environment. The PRISMA offers the advantages of allowing researchers to identify common themes and trends based on both qualitative and quantitative approach without bias under guidance of pre-defined inclusion and exclusion criteria. Only English language journals were searched and selected from Web of Science and Google Scholar collections. The first keywords used was “Uganda Land use”, and then the result was refined with another keyword “cover change”. The study also considered 3 PhD theses, 4 master dissertations giving a total of 42 case studies on LULCC in Uganda. The selected (42) materials from which categories and subcategories were defined for reanalysis are presented in Appendix 1. The findings from the selected 42 literatures were supplemented with data from the Uganda Bureau of Statistics (UBOS) and the World Bank.

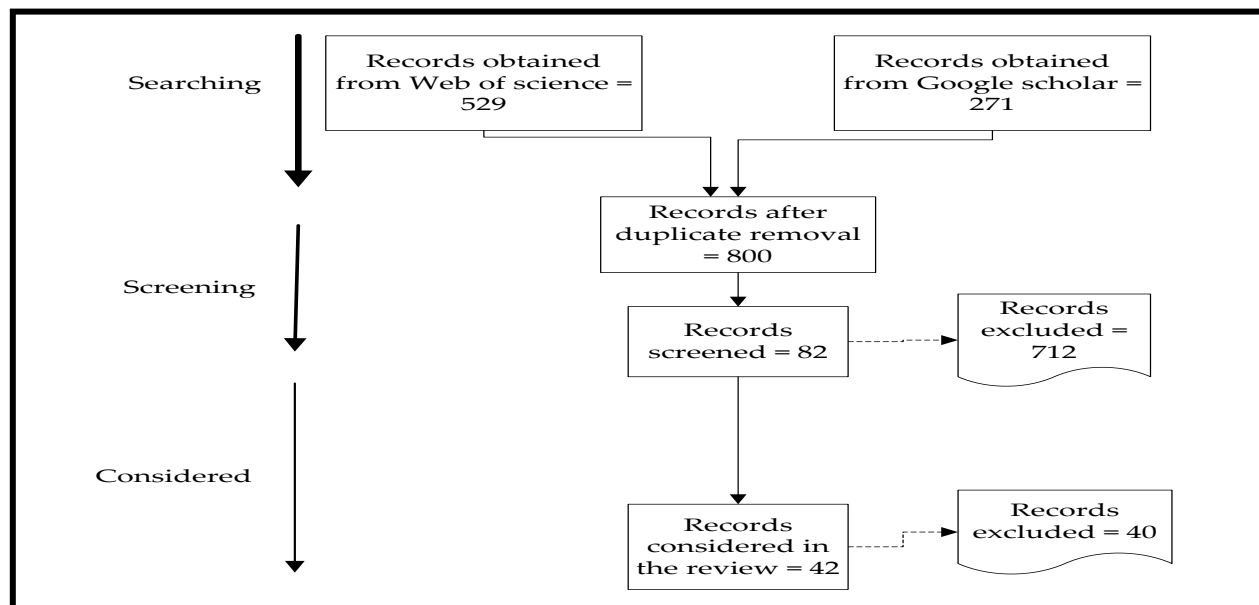


Figure 4.1: Framework within which the review was conducted (modified from PRISMA, 2009)

Information extracted from the reviewed articles was entered in Microsoft Excel 2016 and analysed using descriptive approach. Key categories of extracted information include: author/s-date, where/when the study was conducted, what time frame was covered, what method and data was used by the authors, the key findings in terms of what land use and land cover type decreased/increased, what major drivers and impacts.

4.3 Results and Discussion

4.3.1 Variations of land use land cover studies at regional level

The review revealed that central Uganda is the most studied region with 15 of the case studies, followed by western region (14), eastern region (10), while northern region registered (3) case studies (Figure 4.2). The studies in western Uganda have mainly been conducted in and around Kibale National Game Park and the Albertine region. In eastern Uganda, the studies have mainly been conducted in the Mt. Elgon area and the rangelands of the cattle corridor mainly for conservation purposes. Additionally, some of the studies in eastern Uganda have been motivated by concerns related to landslides disaster (Mugagga et al., 2012), floods, and droughts. In central Uganda, the studies have mostly been driven by the desire to protect the health of Lake Victoria and surrounding wetland ecosystems (Anaba et al., 2017 and Kiggundu et al., 2018). On the

other hand, those in northern Uganda have been conducted to investigate the impacts of past armed conflicts in the region (Nyeko, 2010 ; Gorsevski et al., 2012).

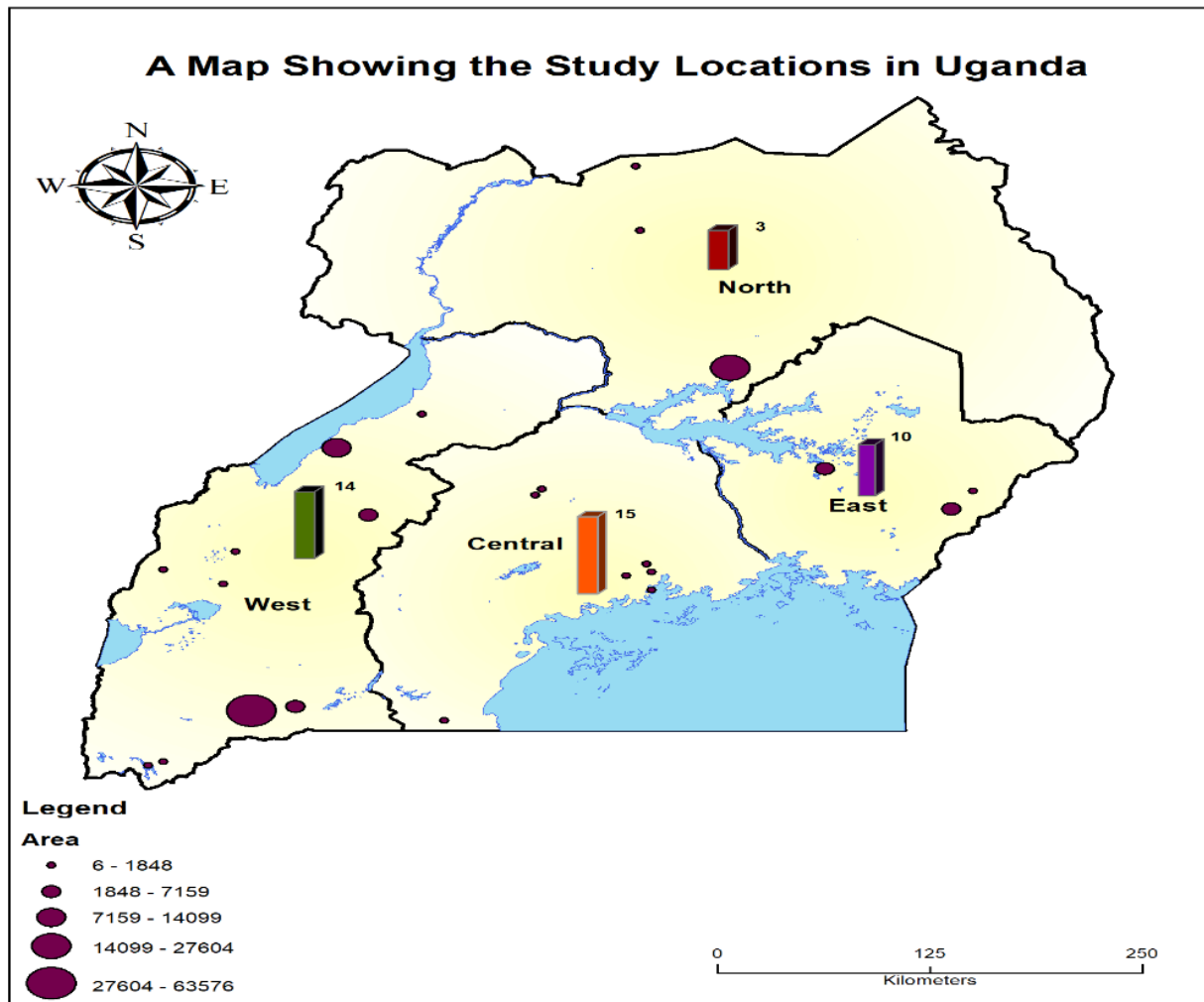


Figure 4.2 Map of Uganda showing locations of the reviewed case studies (extracted and developed based on the review 1998-2018)

4.3.2 Major land use land cover types

Generally, ten major land use land cover types were addressed in the case studies. Of the different land use and land cover types, agriculture, forest, grassland, and woodland were the most commonly reported (Figure 4.3). It is also important to note that beyond the documented ten major land use and land cover, there were other small/detailed breakdown in some land use and land cover types. For example, Mugagga et al., (2012) adopted three broad land-use and land

cover classes namely: forest cover, woodlands and agriculture. Forest was further clustered into plantation coniferous, plantation deciduous, tropical encroached and tropical well stocked. Woodland meanwhile consisted of riparian vegetation, shrubs and bushes. Finally, all cultivated and fallow land was designated as agricultural fields. The review therefore indicates a lack of adoption of a standard land use and land cover classification scheme for Uganda.

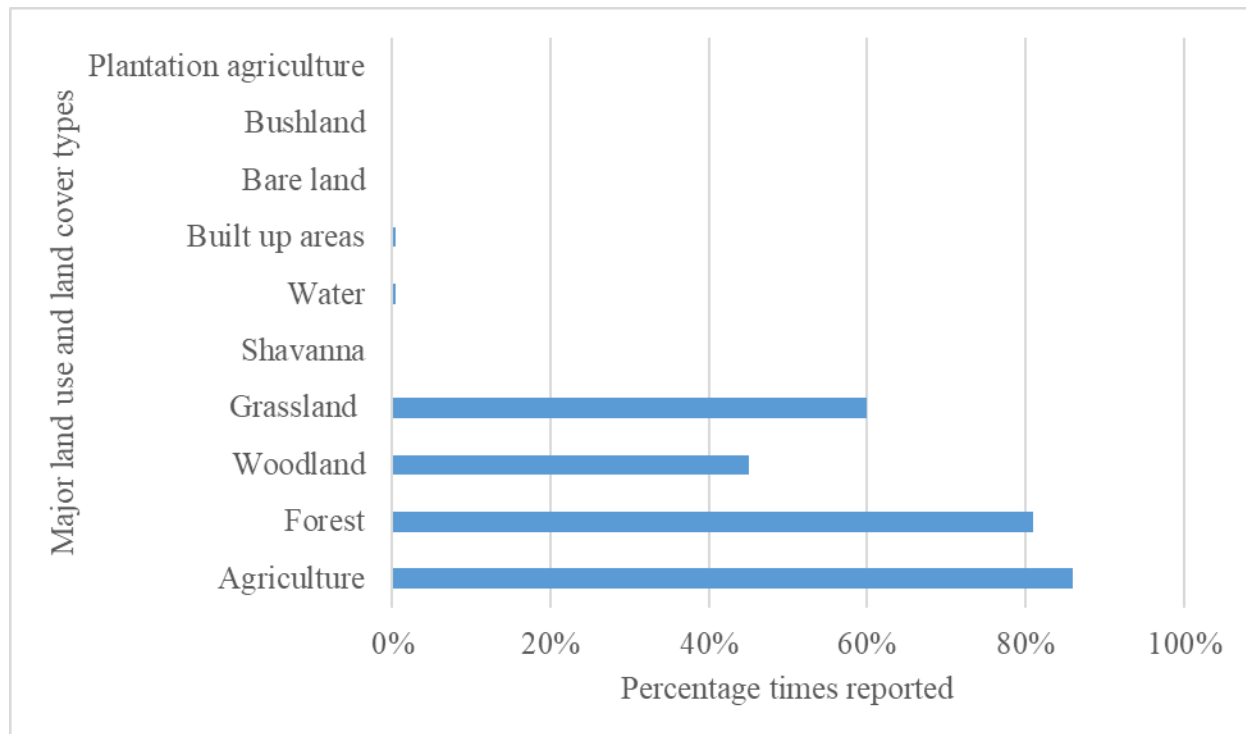


Figure 4.3 Major land use and land cover types reported in the case studies (extracted from the reviewed literature 1998-2018)

4.3.3 Publication trend

In research, the number and growth rate of scientific publications are taken as important science productivity or output indicators (Alvarado, 2015). The current study found that a total of 42 publications were produced in Uganda by 35 first authors (Appendix 1) over a twenty-year period (1998-2018) as seen in (Figure 4.4). The lower end is 1 and the upper end is 8 giving a range of 1 to 8 publications over the two decades. Grouped in decades, (7 %) of the publications were made in the first decade (1998-2008) while (93 %) of the publications came in the second decade (2009-2018). On average, 1.2 papers are produced every twenty years equivalent to 0.6

publication per decade. The mean of publication over the two decades is 3 while the median is also 3 with a variance of 4.6 documents published and standard deviation of 2.1. The growth in number of publications fits an exponential curve with $R^2 = 0.42$. The pattern of growth of literature on LULCC in Uganda agrees with the scientifically documented pattern in studies of literature production over a long period of time (Larsen & von Ins, 2010; Alvarado, 2015). The growth in LULCC literature in Uganda is comparable to that reported by Pham, Turner, & Trincsi, (2015) in northern upland of Vietnam where the authors found that the topic was only 12 years old with only 17 articles published between 2001 and 2013. In Nepal, similar review by Paudel et al., (2016) reported that LULCC studies in Nepal was 30 years old dating back from 1985 to 2015. The authors also reported 10 country scale LULCC studies between 1985 to 2015 and 16 regional and local scale studies from 1990 to 2014.

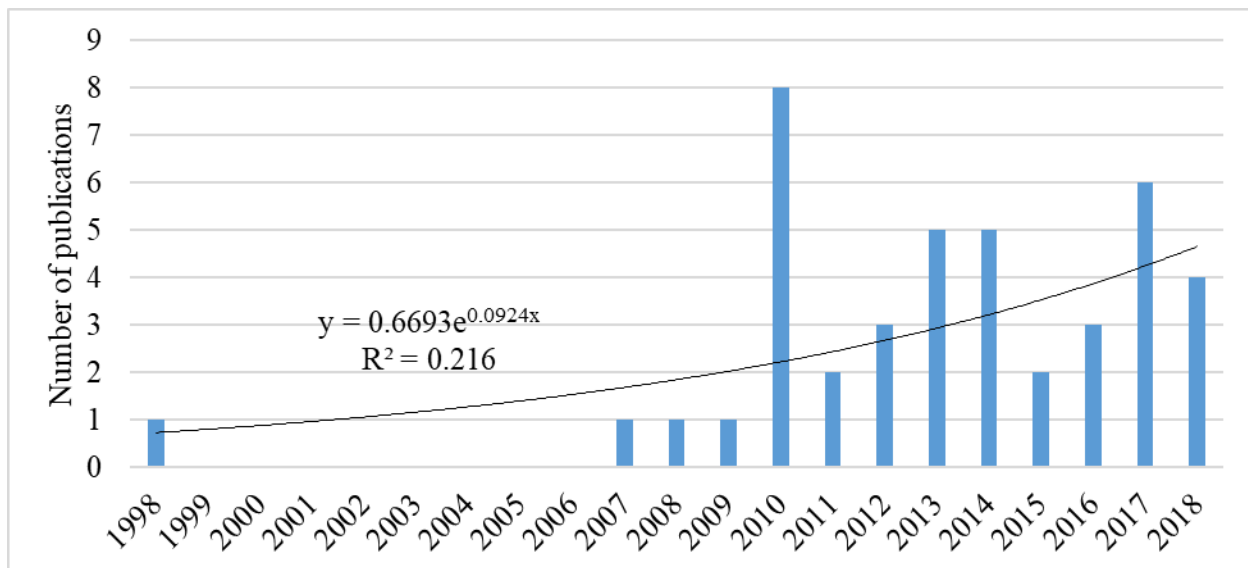


Figure 4. 4 Number of publications per year in Uganda (extracted from the reviewed literatures 1998 to 2018)

4.3.4 Intensity of the studies

The intensity of the studies Figure 4.5 depicts a sigmoid growth curve with period of accelerated growth from 1980-1985 and peaked off from 1995 to 2005 before starting to decline from 2005 to 2015. The period of accelerated growth coincides with the coming to power of the current government in 1986 and the new constitution in 1995. The decline from 2005 to 2015 is because

95% of studies used the earth observation, particularly Landsat imagery (30m resolution) available for downloads for past years not future time period.

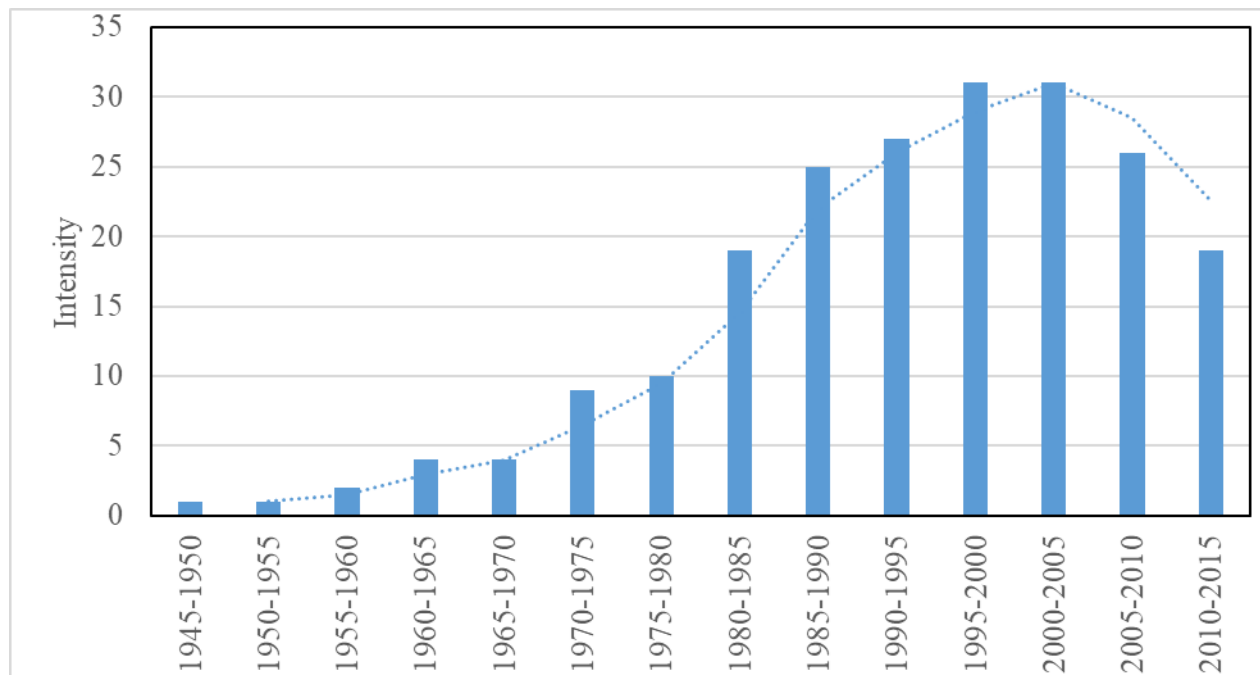


Figure 4.5 Intensity of the studies (extracted from the reviewed literatures 1998-2018)

4.3.5 Time frame of case studies

The case studies covered different time periods with overlaps in some cases (Figure 4.6). The shortest time frame covered was 5 years, the longest was 47 years, the average 23 years while, the mode is 29 years which is almost a climatological period. The earliest time period ever studied in Uganda was 1945 while the latest is 2015. The most studied time frame ranged from about 1980 to 2010. The observed concentration of study time frame starting from 1980 to current can locally be linked with the coming of the National Resistant Movement (NRM) into power in 1986. The NRM government brought in a new Constitution in 1995, which resulted into many policies and laws relating to environmental conservation being developed and implemented. In other parts of the world, Paudel et al., (2016) in Nepal and Pham et al., (2015) in upland northern Vietnam found that most LULCC studies covered the period between 1985 and 2005.

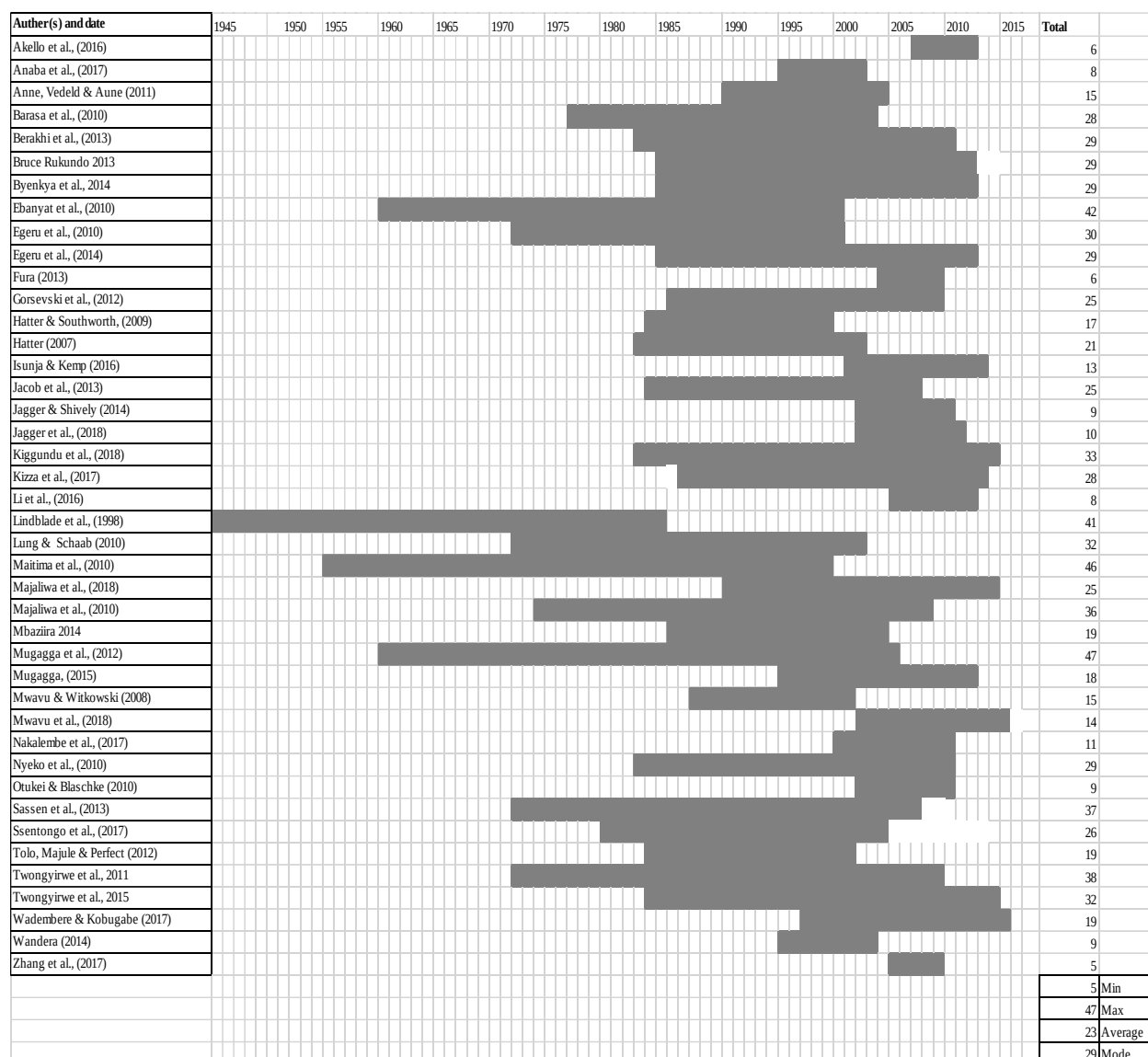


Figure 4.6 Time frame of the case studies (extracted from the reviewed literatures 1998-2018)

4.3.6 Scales of the studies

Uganda is divided into administrative units: national, regional, district, county, sub county, parish, and finally villages. In addition to the administrative units, this study also dealt with catchment (an area drained by a water body), forest, and national parks. Results indicate that the most preferred scale of studies was the district (48 %), followed by the catchment (19 %), forest (17 %), national and national park scales (10 %) and (7 %) respectively (Figure 4.7). District scale studies have been motivated by many reasons including but not limited to land use change

and drivers (Nakalembe, Dempewolf, & Justice, 2017), extent and trend of LULCC (Egeru & Majaliwa, 2010), and commercial agriculture against food security (Mwavu et al., 2018). On the other hand, all catchment scale studies have directly or indirectly focused on impacts of LULCC on water resources. For example, Anaba et al., (2017) looked at water quality under various land use changes, Isunju & Kemp, (2016) investigated the spatiotemporal encroachment on wetlands in Nakivubo wetland in Kampala, Uganda. Forest and National park scales studies have been related to conservation efforts (Sentongo, Darkey, & Mutyaba, 2017, Sassen, et al., 2013). The reasons for the national scale studies have been to: understand the spatial and temporal land use and carbon stock changes in Uganda (Nakakaawa, Vedeld, & Aune, 2011), assess the extent of historical, current, and future land use systems in Uganda (Majaliwa et al., 2018), assess the impacts of land use and land cover change on terrestrial carbon stocks in Uganda (Zhang et al., 2017), and examine historical and future land use changes in Uganda (Li et al., 2016).

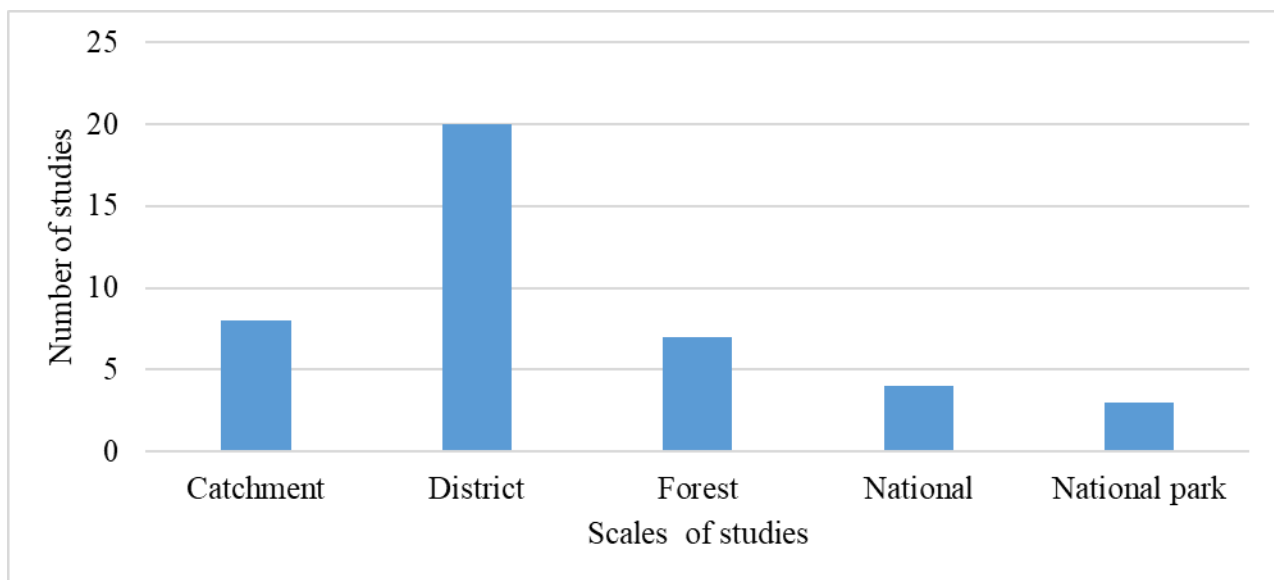


Figure 4.7 Scales of the case studies (extracted from the reviewed literatures 1998-2018)

4.3.7 Methods and data employed in the studies

The most used method/data was earth observation, particularly Landsat imagery (30m resolution) employed in 95.2 % of cases, MODIS (250m and 500m) employed in 2.4 % of cases, and transect walk plus interview in 2.4 % of studies (Figure 4.8). This might be because Landsat 30 m was the highest resolution until 2017, when the Sentinel 2 Satellite data became available for free downloads.

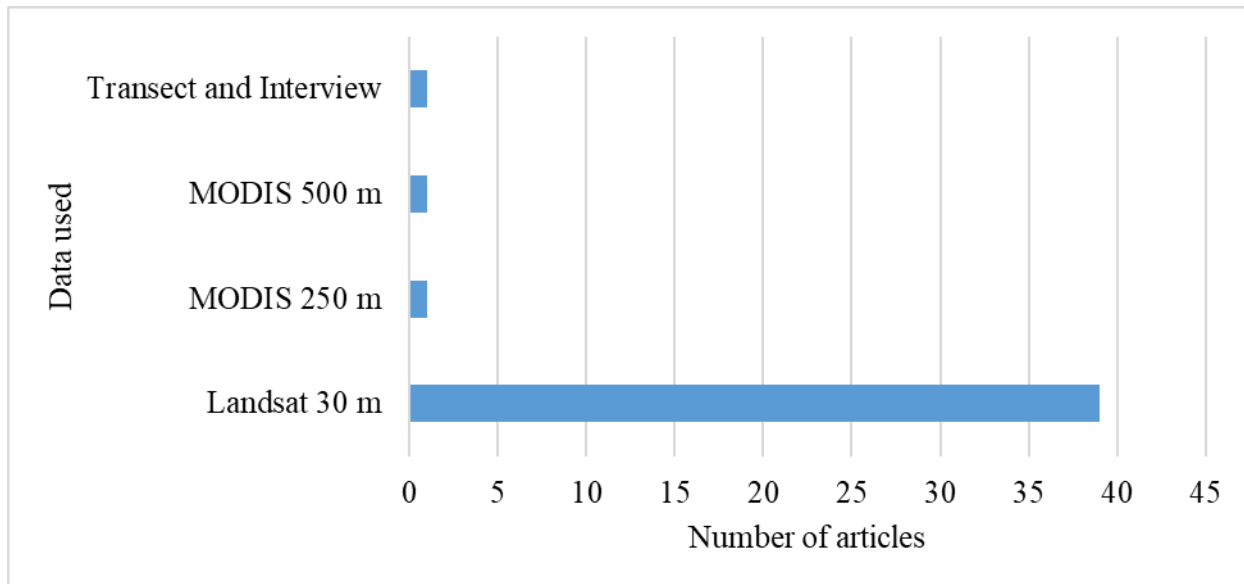


Figure 4. 8 Data/methods used in the case studies (extracted from the reviewed literatures)

4.3.8 Land use land cover change in Uganda

Results show that agriculture and built-up areas (from here on used interchangeably with settlements) have increased while forest and woodland have decreased over the period (1998-2018). This trend is also supported by data from UBOS (2019) (Table 4.2). The table indicates that built-up areas increased from about 365 km² in 2005 to 670 km² in 2010 and to 1360 km² in 2015. Agricultural lands meanwhile increased from 84,695 km² in 1990 to 95,211 km² in 2000 then to 100,000 km² in 2005-2010, and finally to 105,317 km² in 2015. Forest decreased in area from 49,334 km² in 1990 to 36,655 km² in 2005, and finally to 19,535 km² in 2015. Wetlands change however, has been case specific with local studies reporting a mix of increasing and decreasing trend as later discussed. However, on a national scale, wetland area appears generally stable. According to the Ministry of Water and Environment (MW&E, 2015), Uganda lost on average 122,000 ha/year of forests between 1990 and 2015, in favour of agricultural area expansion. Similarly, national area of wetlands declined by 30 % between 1994 and 2008, and slightly increased by 0.03 % between 2008 and 2014. The numbers of urban centres increased from 67 in 1991 to 259 in 2014, while urban population increased from 0.6 million people in 1969 to 6.4 million people in 2014 (UBOS, 2014). The implication is that the interaction of population growth and other drivers of LULC change is favouring agricultural and built-up/urban areas expansions at the expense of forests, woodlands, wetlands, as later discussed.

Table 4. 2 National land cover areas (Km²) between 1990 and 2015

Type of land cover	Km ² 1990	in Km ² 2000	in Km ² 2005	in Km ² 2010	in Km ² 2015
Built-Up Areas	365.7	365.7	365.7	969.79	1360.02
Bush-lands	14,223.90	12,624.50	11,893.60	23,776.05	19,723.25
Agriculture	84,694.50	95,211.20	99,703.10	99,219.98	105,317.21
Commercial Farmlands	684.5	684.5	684.5	1343	2567.46
Cultivated Lands	84,010.00	94,526.70	99,018.60	97877	102,749.75
Grasslands	51,152.70	51,152.70	51,152.70	50,859.25	51,051.57
Impediments	37.1	37.1	37.2	114.21	78.56
Forest	49,333.60	40,416.40	36,654.80	21,943.20	19,535.30
Woodlands	39,740.90	32,601.40	29,527.80	14449	12,144.78
Plantations - Hardwoods	186.8	153.3	138.6	213	442.98
Plantations - Softwoods	163.8	80	121.5	442	635.68
Tropical High Forest	2,740.60	2,248.20	2,036.30	5637	1,020.00
Tropical High Forest Normal	6,501.50	5,333.50	4,830.60	1202	5,291.86
Water Bodies	36,902.80	36,902.80	36,902.90	36,581.00	36,864.01
Wetlands	4,840.40	4,840.40	4,840.60	8,087.00	7,620.76
Total	241,550.70	241,550.70	241,550.70	241,550.70	241,550.70

Source: UBOS data downloaded on 22/09/2019

On local scales, Barasa et al, (2011) reported increase in agricultural lands and decrease in forests between 1975 and 1999 in western Uganda. Similar trend was also reported in the same region by Majaliwa et al., (2010) between 1973 and 2009. In eastern Uganda, Mugagga et al., (2015) reported increased agricultural lands at the expense of forests between 1960 and 2006. Increase in agricultural lands and urban areas expansion was also reported between 1987 and 2005 by Mbazira, (2014), and between 2007-2013 by Akello et al., (2016) in eastern Uganda. In central Uganda, a similar trend was reported between 1995- 2003 by Anaba et al., (2017), while in northern Uganda Nyeko, (2010) reported a decrease in agricultural lands over the period 1986-

2001. The reported trends also confirm what is observed at national level, except for the Acholi sub region (northern Uganda).

Note that the trends of forests cover and agricultural lands in northern Uganda are different from the national trend and those in other regions. First, only 9.5 % of the reviewed LULCC studies were from northern Uganda. Fewer studies meant less representation of the actual situation on the ground. Northern Uganda also experienced armed conflict from 1986 to mid-2000s. During the period of the armed conflict, people were restricted to live in Internally Displaced Person's camp (IDP's). The people had little or no access to their land, and could therefore not exploit the resources therein. With return of peace in northern Uganda, IDP's life ended in the late 2008. There are now good roads linking all parts of the region to the grater markets within Uganda, and with South Sudan and DR. Congo. There has also been rapid expansion of commercial farming in the northern districts of Nwoya and Amuru in the last ten years. The dynamics and the trajectory of LULCC in northern Uganda have thus changed. It is not surprising that the study of Gorsevski et al., (2012) found high rate of deforestation in northern Uganda coinciding with the time after life at the IDPs camps.

4.3.9 Drivers of land use land cover change

Only 38 % of the studies analysed the drivers of LULCC. However, even articles that did not analyse LULCC drivers have alluded to some or all the drivers as responsible for observed change (Figure 4.9). The Figure also indicates that population and agricultural area expansions are the most reported major drivers of LULCC in Uganda. For example, Anaba et al., (2017) and Wandera, (2014) in central, Wadembere & Kobugabe, (2017) and Hartter & Southworth, (2009) in western, and Gorsevski et al., (2012) in northern Uganda all emphasized population pressure as the main driver of LULCC. However, Nakalembe et al., (2017) found that it was lack of policy implementation but not population pressure driving LULCC in northern Uganda. On the other hand, Nyeko, (2010) reported insecurity as the major driver of LULCC in northern Uganda and not population or policy implementation. In eastern Uganda, Place & Otsuka, (2000) discussed unemployment to be the key driver of LULCC, whereas according to Mugagga et al., (2015), it was population and lack of cultivatable land driving LULCC in eastern region. On a national scale however, increased demand for forest products, lack of policy implementation, and

agricultural area expansion have been reported as major drivers of LULCC in addition to population Li et al., (2016), Zhang et al., (2017), and Jagger & Kittner, (2017).

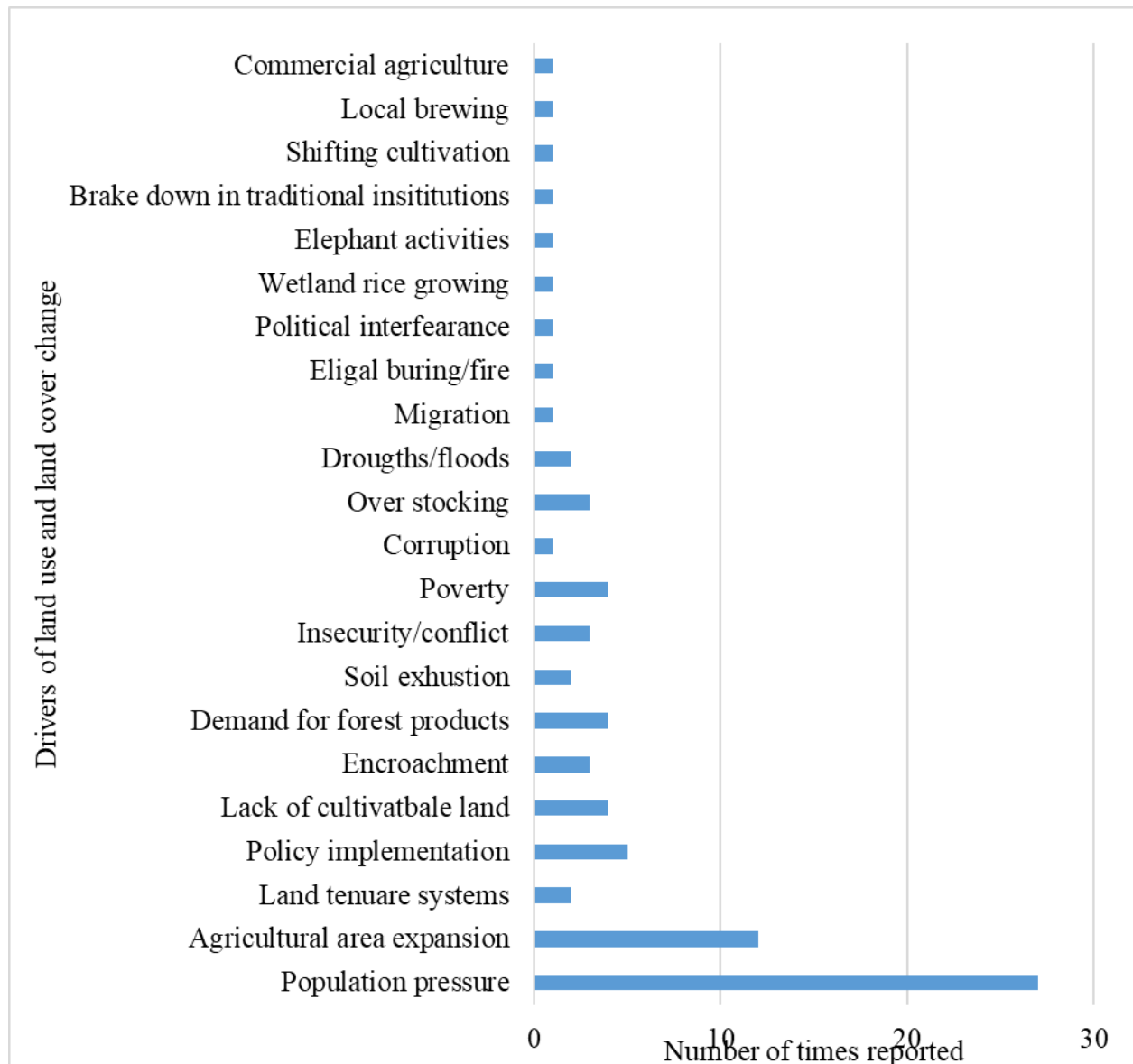


Figure 4.9 Reported major drivers of land use and land cover change (extracted from the reviewed literature 1998-2018)

4.3.10 Interactions between drivers of land use land cover change

The review indicates that the major drivers of LULCC do not operate in isolation but rather in unison. For example, the population of Uganda grew from 6.8 million people in 1960 to 34.6 million people in 2014, and it is projected to reach 80 million people by 2040 (UBOS, 2014).

With a growth rate of 3 % per annum, Uganda has the third fastest growing population in the world (United Nations Population Fund (UNFPA), 2017). Increased population led to increased demand for natural resources, which affected LULCC in different ways. For instance, increased population meant more food, housing, jobs, and other environmental resources required. Forest and woodland therefore got cleared for reasons such as agriculture, settlement, biomass products etc. as reported by Mugagga et al., (2012), Mugagga et al., (2015), and Barasa et al., (2011). In general terms, it explains why increased agriculture and built-up areas have been reported at the expense of forest, wetland, woodland etc. on local and national levels in the reviewed articles. Similarly, increase in population was accompanied by increased unemployment. Unemployment increased from 1 % in 1991 to 3.6 % in 2003 where it again dropped to 1.9% in 2005 before increasing to 3.6 % in 2009 although the current figure is 1.7 % (World Bank, 2019). With unemployment, rural to urban migration increased as people search for better livelihoods opportunities in urban areas. Consequently, Anaba et al., (2017), Akello et al., (2016) and Wandera, (2014) reported increased built-up areas in different places and times. When the resources get over constrained, especially in urban areas, people (especially the poor) are forced to settle in or cultivate wetlands. Wetland decline has been reported in western, central, and eastern Uganda. In the above regions population are higher and total land areas are smaller compared to northern Uganda (Table 4.1).

In Uganda, agriculture is a key sector to the livelihoods of the rural population (79 % of total population) and to the economy of Uganda (UBOS, 2018). Accordingly, in the year 2013/14 and 2015/16, agriculture employed 74.7 % and 73 % of total rural labor force respectively and the sector's contribution to total GDP increased from 23.7 % in 2015/16 to 25 % in 2016/17 (MAAIF, 2017). No doubt, agriculture is making tremendous contributions to the livelihoods of the rural population and total GDP of Uganda. The rapid population growth and economic drivers have increased demand for forest products, agricultural and urban areas expansion, manufacturing and construction industries among others (Majaliwa et al., 2018). The demographic and socio cultural, economic and diversity in the landscapes have escalated LULCC in many parts of Uganda. Additionally, land available for agriculture has become increasingly scarce in many parts of the country and has forced subsistence farmers to encroach on marginal lands and protected areas (Mugagga et al., 2013 and Mugagga et al., 2010).

As already discussed, the population of Uganda is projected to more than double by 2040. Based on analysis of drivers of LULCC, this can be translated as more pressure on the fixed land resources by 2040. The demographic trend and desire for socioeconomic growth in Uganda may continue to drive LULCC in the country. Similarly, Majaliwa et al., (2018) discussed in detail the projected land use systems in Uganda in 2040. Most importantly, their key finding indicates that agricultural land area will generally increase in 2040 with commercial agriculture increasing by 1.19% and irrigated agriculture by 0.04 %. Subsistence agriculture will still remain the most dominant land use system increasing by 45.45 % in 2040. Woodland/unprotected forest will decrease from 867.25 km² in 2015 to only 287.27 km² in 2040, representing a drop of 0.12 %. Li et al., (2016) meanwhile found that agricultural land will increase while forest land will decrease in the country in 2025 under both businesses as usual and deforestation scenarios.

4.3.11 Impacts of land use land cover change

LULCC is having a wide range of impact on the environment and the people of Uganda at different spatial and temporal scales. For example, Barasa et al., (2011) reported that decrease in forest, wetland, and woodland as a result of increased agriculture between 1975 and 1999 resulted in reduced tree species diversity in western Uganda. In the Mt. Elgon area in eastern Uganda, Mugagga et al., (2015) noted that increased farmland at the expense of forest has led to land with high carbon stocks and reduced the potential of Mt. Elgon areas as a carbon sink. Similarly, Akello et al., (2016) reported that between 2007 and 2013 deforestation, wetland encroachment, poor attitudes, population pressure, and political interference led to poor water quality and lack of formal jobs in Ngora district in eastern Uganda. On the other hand, Egeru & Majaliwa, (2010) reported decline in forage quality, reduced grazing area, and increased floods and drought in Teso in eastern Uganda between 1973 and 2001. In the Machismo bay, central Uganda, Anaba et al., (2017) reported increased flooding, water quality decline, and reduced crop yield between 1995 and 2003. Between 1973 and 2009, Majaliwa et al., (2010) reported changes in soil properties as a result of increased agriculture, increased demand for fuelwood, and population pressure in western Uganda. In other parts of Uganda, LULCC was reported to have had negative effects on total fuel consumed (Jagger & Shively, 2014), as well as reduced slope stability affected by hydrological conditions triggering debris flows (Mugagga et al., 2012), threatened conservation and chimpanzees (Mwavu et al., 2008). LULCC also increased

water quality degradation resulting into increased water treatment cost (Anaba et al., 2017), increased waterborne diseases and reduced ecosystem benefits (Jagger & Kittner, 2017).

4.4 Conclusions

This study systematically reviewed 42 LULCC studies in Uganda from 1998 to 2018 based on the framework of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. The aim was to document and synthesis the findings to shed light on the impacts and the drivers of LULCC at regional scales. From the key findings, the study concluded that:

1. Between 1998 and 2018, LULCC studies in Uganda covered different spatiotemporal scales and the most used data has been Landsat 30 m.
2. Generally, agricultural lands and built-up areas are increasing at the expense of forests, wetlands and woodlands.
3. Population pressure stands out of all as the key drivers of LULCC on a national, regional and local scale.
4. The magnitudes and impact of LULCC differ in both space and time within Uganda.
5. The 1998-2018 trends of LULCC and related impacts in Uganda are likely to continue, as the projected population is likely to double by 2040.

4.5 Recommendation

1. Stakeholders at different levels need to integrate local context socioeconomic, cultural, and environmental settings in the design and implementing policy relating to land resources management to ensure the sustainability of the resources and livelihoods.

CHAPTER FIVE: DYNAMICS OF LAND USE LAND COVER IN SIRONKO CATCHMENT ON A MEDIUM TIME SCALE

5.1 Abstract

Monitoring and projecting LULCC are important for the sustainability of landscapes. This study determined the dynamics of land use land cover change in Sironko catchment between 1986-2016) and (2016-2040) using intensity analysis and the Markov-Cellar Automata process. Landsat images were analysed by supervised classifications and generalisation techniques using maximum likelihoods algorithm. Change detection was achieved by post classification change detection technique. The maps were overlaid to generate cross-tabulated transition matrix. Future land use and land cover were projected by the Markov Cellular Automata (Markov-CA) in the Land Change Modeler (LCM) of the Tera Sat. Results show that agricultural land; forests; and wetlands areas reduced by 8 %; 32 %; and 20 % between 1986 and 2000 while built up areas increased by 40 % in the same period. But between 2000 and 2016, forests, wetlands, and built-up areas increased by 84 %, 5 %, and 57 % while, woodlands and agricultural land decreased by 43 % and 13 % respectively. The huge increase in forests was a result of eviction of community from encroached forest lands. From 2016 to 2040, built-up areas will increase by 72 %; agricultural land by 5 %; and grasslands by 2 %; while wetlands will decrease by 9 % and woodlands by 7 % respectively. Transition to agriculture between 1986 and 2000 and 2000 and 2016 targeted built up areas, forests, grasslands, woodlands, and wetlands. On the other hand, transition to forests targeted agricultural land, grasslands, and wetlands areas between 1986 and 2000 but between 2000 and 2016, it only targeted agricultural land and woodlands. Likewise, woodlands targeted all the land use and land cover categories between 1986 and 2000 but, between 2000 and 2016 it targeted bare lands, built up areas, forests, and grasslands areas only. Available land for agriculture is under significant pressure as a result of built-up areas expansion. Local communities have to be educated and encouraged to continue practicing soil conservation measures in Sironko catchment while, land resources management in the catchment and Mt. Elgon region should not only focus on the landscape composition but also pay attention to landscape configuration and livelihoods means of the local people.

5.2 Introduction

Land use land cover change (LULCC) is a key issue of concern on global environmental change and sustainable development agenda due to its impacts on ecosystems and livelihoods (Yirsaw et al., 2017). Although natural factors also contribute to LULCC, human footprints such as overexploitation of forests, agricultural intensification, overgrazing, urbanization and the subsequent land degradations have caused natural resource shortages and widespread losses of biodiversity across the globe (Pickard et al., 2017; Yirsaw et al., 2017). Hence, LULCC studies are required to address the increasing anthropogenic pressure on land resources. In the 21st century, particular attention is being given to LULCC occurring at local scales because it adversely affects the ecosystems leading to potential economic and social impacts on local communities with ripple effects on regional and global scales (Lu et al., 2019). Understanding the dynamics of land use and land cover at a catchment scale is therefore, vital for guiding the selection, planning and sustainable management of land resources to meet the increasing demands for basic human needs and livelihoods (Tewabe & Fentahun, 2020).

In most developing countries, LULCC is mainly driven by population growth (Tewabe & Fentahun, 2020). Uganda for example has a young and rapidly growing population of 36.4 million, growing at above 3.03 % per annum, and is projected to reach 80 million by 2040 (UNFPA, 2017; UBOS, 2016). However, over 80 % of the population directly obtain their livelihood from environmental resources such as forest, wetlands, water, and grasslands (UBOS, 2016). As a result, population pressure and other socio-economic drivers are leading to unprecedented LULCC changes at different spatial and temporal scales in the country (UBOS, 2016). Uganda is also so diverse in terms of the landscapes, sociocultural and economic settings, which are all catalysts for accelerated LULCC. Given this background, government agencies and policy makers may need to invest in redesigning current land use policies and/or develop new approaches so that the policies meet specific local context with specific drivers, causes, and impacts (Luwa et al., 2020). Many LULCC studies have been conducted in Uganda at different spatiotemporal scales and for different (Majaliwa et al., 2018; Kiggundu et al., 2018; Zhou et al., 2017; Jagger & Kittner, 2017; ; Kizza et al., 2017; Akello et al., 2016; Li et al., 2016; Mugagga et al., 2015; Jagger & Shively, 2014; Egeru et al., 2014; Mugagga et al., 2012; Twongyirwe et al., 2011; Barasa et al., 2011; Majaliwa et al., 2010). In summary, these studies suggest that

LULCC in Uganda is a complex phenomenon driven mostly by population growth and the demand for both agricultural land and forest products (Luwa et al., 2020).

Sironko catchment on Mt. Elgon is a major headwater source supporting millions of lives in the catchment specifically and the Lake Kyoga basin at large. However, the catchment lies within a fragile ecosystem (the Mt. Elgon region) where rapid LULCC is being experienced (Mugagga et al., 2015; Mugagga et al., 2012). The Mt. Elgon region is also prone to hazards such as soil erosion, landslides, floods, and drought (Knapen et al., 2006). Additionally, (UBOS, 2016) revealed that Mt. Elgon region is one of the poorest and most densely populated, and rapidly urbanizing rural part of Uganda. The socioeconomic and demographic status of the people around Mt. Elgon force them to encroach on protected areas and forest reserves on the mountain, and to cultivate ecologically fragile areas such as steep slopes, swamps, and riverbanks (Nakileza et al., 2017). The situation calls for a clear linkage of the land change patterns to the processes underlying the change and understanding the mechanisms of change, to aid the generation and predictions of future rates of change, and to facilitate policy design in response to the change (Akinyemi et al., 2017).

Recognising that LULCC in Uganda is heterogeneous in terms of patterns, magnitudes and impacts Luwa et al., (2020), it becomes difficult to generalise the LULCC trends in the country. More so, policy makers may be misled if such attempts are made. Site-specific LULCC analyses in Uganda are therefore crucial to extract vital information on land use and land cover dynamics and future scenarios to support localised decision-making regarding land use planning and management. However, previous studies in Mt. Elgon region have only been limited to the usual change detection analysis (Mugagga et al., 2015; Mugagga et al., 2012). The usual change detection analysis has become mundane and adds little value to land use and land cover literature, policy, and practice (Akinyemi et al., 2017; Aldwaik & Pontius, 2013, 2012). The Sironko catchment therefore, requires an in-depth analysis of LULCC to bring out more nuances and address questions such as: which of the land category/class systematically targeted another category to expand? Which of the time interval was fast or slow? Which of the categories experienced active dormant change? These questions can be addressed using Intensity Analysis (Aldwaik & Pontius, 2013, 2012).

This study examined the spatiotemporal configuration of LULCC in a fragile tropical mountain environmental context in Africa in order to detect the principal signals of such changes. Going beyond mapping of LULCC to reveal the relative amounts of land under various land categories, the study quantified the dynamics of land use and land cover in Sironko catchment during two time intervals (1986-2000 and 2000-2016) using the Intensity Analysis framework (Aldwaik & Pontius, 2013, 2012) and projected the land use and cover scenario in 2040 by the Markov-Cellar Automata process.

5.3 Materials and methods

5.3.1 Study area

This study was conducted in Sironko catchment, Mt. Elgon region, Uganda (Figure 3.1 in chapter 3). For detailed description of the study area is presented in chapter 3, section 3.1.1-3.1.5

5.3.2 Land use land cover data

To obtain the land use and land cover maps of Sironko catchment in 1986, 2000, and 2016, satellite images for the respective years were used. The images with less than 10% cloud cover were downloaded from the United States Geological Survey (USGS) website <http://earthexplorer.usgs.gov/>. Table 5.1 gives a summary of the characteristics of the satellite images used.

Table 5.1: Details of the Landsat satellite imagery data

Landsat instrument	Spatial resolution (m)	Sensor	Path	Row	Date acquired
Thematic Mapper (TM)	30	LT05	170	59	08/03/1986
Enhanced Thematic Mapper (ETM)	30	LE07	170	59	06/03/2000
Operational Land Imager (OLI-TIRS)	30	LC8	170	59	23/02/2016

5.3.3 Image pre-processing

The images selected were for dry season months where cloud effects on the images were practically minimal (less than 10 %). Subset of the images for the catchment was extracted by

mask using a shape file for the catchment. Landsat images are supplied in pre-processed forms including geo-referencing and ortho-rectification. More so, atmospheric correction was not needed since the land use and land covers were analyzed using post classification comparison technique which also compensates for variations in atmospheric conditions and vegetation phenology between the dates, given that each land use/cover classification is independently mapped (Mugagga et al., 2012; Yuan et al., 2005; Coppin et al., 2004). However, 20 ground control points obtained from google earth image were used to further improve the geo-rectification accuracy. The Landsat imagery were resampled in ArcGIS 10.2 environments, using the nearest-neighbor technique; and the residual values ranged from 0.0001 to 0.001 pixels (Mugagga et al., 2012). The radiometric correction of the images was carried out using the ‘CALIBRATE’ module in ArcGIS. The imagery was visually enhanced by processing 8-bit composites with original values and stretched to saturation points (Mugagga et al., 2012).

5.3.4 Land use and land cover classification

The images were classified for the study area using maximum likelihood classifier of supervised classification in ArcGIS 10.2. In supervised classification, signatures files were created for different land use and land cover classes by picking representative areas with known land use land cover classes as training areas to describe the spectral profile of feature type of interest. Maximum likelihood algorithm was implemented to identify different land use land cover classes. A majority filter process was used to remove isolated pixels or noise from the classification output. The filter merged areas of mixed pixel values into a big area of the more predominant value.

The land use land cover of the study area were classified into seven major classes: agricultural land, bare land, built up areas, forests, grasslands, wetlands, and woodlands (Appendix 2) based on Anderson et al., (1976) level I classification (Table 5.2). The Anderson et al., (1976) level I classification scheme was used as it includes the most general classification for broad land use categories such as ‘agricultural land’ or ‘urban/built-up’ areas. Within each level I class, are also a number of more detailed level II land use land cover classes e.g., ‘the urban/built-up’ classes included residential, commercial, and industrial sub classes. For the purpose of this study, the level I classification was found to be sufficient.

Table 5 2: Land use land cover classification system: Adopted from Anderson et al., (1976)

Anderson 1976 land use land cover classes (level I)	Current study land use land cover classes	Description (level II)
Urban or built-up land	Built-up areas	Residential, small towns, villages and highways
Non-forested Wetland	Wetlands	Wetlands areas with extensive permanent reed vegetation such as Papyrus
Agricultural land	Agricultural land	Areas planted with perineal and non-perennial crops (Banana, coffee, maize, beans, cassava, sweet potatoes etc.).
Rangeland	Grasslands	Areas dominated by grass and short scattered shrubs or vegetation. In some period of the year some parts maybe water logged
Rangeland	Woodlands	Areas dominated by trees either indigenous, planted or both. The tress are not densely packed and not as tall as those in forest
Forest	Forests	Area covered with dense natural forest and/or plantation forest, it includes eucalyptus trees, pine trees and other mixed indigenous bush and trees species
Barren land	Bare lands	Rocky areas with thin soil layer and low or no vegetation, consists of vulnerable soil to erosion and degradation and unable to support cultivation

5.3.5 Ground truth survey and accuracy assessment

To support accuracy assessment of the classifications, a ground truth survey was conducted in the study area in December 2017, to geo-reference the different land use land cover classes identified in the image analysis using the Global Positioning System (GPS). The 118 GPS

control points were used for accuracy assessment of the image analysis (Tadele et al, 2017; Goudarzi & Landry, 2017). Furthermore, the researcher's knowledge of the study area was also used in the reconstruction of past land use and land cover.

The overall accuracy was calculated by dividing the total number of correct pixels (diagonal values) by the total number of pixels in the confusion matrix. Overall accuracy gives the overall results of the confusion matrix. Kappa coefficient was used to measure the agreement between the classified image and a set of field survey sample points (Table 5.3). Overall classification accuracy and Kappa coefficient were determined using Equations 5.1 and 5.2, respectively (Landis & Koch, 1977).

$$\text{Overall accuracy} = \frac{\text{Sum of correctly classified samples}}{\text{Sum of all samples}} \times 100 \quad (5.1)$$

$$K = \frac{\sum_{i=1}^k \pi_{ii} - \sum_{i=1}^k \pi_{i+} \pi_{+i}}{1 - \sum_{i=1}^k \pi_{i+} \pi_{+i}} \quad (5.2)$$

Where; K is the Kappa coefficient, k is total number of counts in the confusion matrix, π_{ii} is the number in row i and column i , π_{i+} is sum of row i , π_{+i} is the sum of column i . The K statistics have values ranging from 0 – 1, although negative values are possible but rare. K values closer to 1 indicate almost perfect agreement Landis & Koch, (1977) see (Table 5.3).

The accuracy of the classification for the classified maps of 1986 and 2000 were unmeasurable, due to lack of ground information. According to Enaruvbe & Pontius (2015), this situation commonly arises especially when it is impossible to obtain ground information for the maps derived from the distant past. However, for the 2016 map, the overall accuracy; user's accuracy; producer's accuracy; and Kappa coefficient were assessed based on 7 * 7 confusion matrix.

Table 5.3: Agreement between classified and reference images.

Kappa statistic	Strength of agreement
<0	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial
0.81-1.00	Almost perfect

Source: (Landis & Koch, 1977).

5.4 Land use land cover change intensity analysis

The traditional transition matrix can only communicate the sizes of land transitions. However, application of Intensity Analysis deepens land use land cover analysis to link patterns with process (Aldwaik & Pontius, 2013). According to Aldwaik & Pontius, (2012), Intensity Analysis is an accounting framework to describe the behavior of a categorical variable across time intervals and to measure the degree to which changes are non-uniform at various levels of detail. The uniqueness of Intensity Analysis is in its ability to show whether and observed transition from one category to another deviates from an apparent uniform process (Akinyemi et al., 2017; Aldwaik & Pontius, 2013, 2012). Intensity Analysis is implemented at three levels: the interval level, the category level and the transition level. The interval level compares the overall change during one interval to the overall change during other interval(s). The category level describes the variation in gross loss intensity and gross gain intensity among categories within each time interval. The transition level describes the variation in intensity with which the gain of a particular category transitions from other categories within each time interval (Aldwaik & Pontius, 2013, 2012).

In this study, Intensity Analysis was implemented using five equations whose notations are shown in Table 5.4 (Aldwaik & Pontius, 2013, 2012). Equation 5.3 calculates the speed of change during an interval, which is the size of the change divided by the duration of the time interval expressed as a percentage of the spatial extent. Equation 5.4 calculates a category's annual gross loss intensity during an interval, which is the size of the category's annual gross loss divided by the size of the category at the initial time point of the interval. Equation 5.5

calculates a category's annual gross gain intensity during an interval, which is the size of the category's annual gross gain divided by the size of the category at the latter time point of the interval. At the category level for each interval, the uniform hypothesis is that all categories experience gross loss and gross gain with the same annual intensity, which is equal to the speed of change during the interval i.e., If $S_{ti} < S_t$, then the loss of i is dormant during interval t ; similarly, if $G_{tj} < S_t$, then the gain of j is dormant during interval t . If $L_{ti} > S_t$, then the loss of i is active during interval t ; similarly, if $G_{ti} >$, then the gain of j is active during interval t (Table 5.4).

Table 5.4: Mathematical notations used for intensity analysis

Symbols	Descriptions
T	number of time points
Y_t	year at time point t
t	index for the initial time point of interval $[Y_t, Y_{t+1}]$, where t ranges from 1 to $T-1$
J	number of categories
i	index for a category at an interval's initial time point
j	index for a category at an interval's latter time point
n	index for the gaining category for the selected transition
C_{tij}	size of transition from category i to category j during interval $[Y_t, Y_{t+1}]$
S_t	annual change during interval $[Y_t, Y_{t+1}]$
G_{tj}	intensity of annual gain of category j during interval $[Y_t, Y_{t+1}]$ relative to size of category j at time $t+1$
L_{ti}	intensity of annual loss of category i during interval $[Y_t, Y_{t+1}]$ relative to size of category i at time t
R_{tin}	intensity of annual transition from category i to category n during interval $[Y_t, Y_{t+1}]$ relative to size of category i at time t
W_{tn}	uniform intensity of annual transition from all non- n categories to category n during interval $[Y_t, Y_{t+1}]$ relative to size of all non- n categories at time t

Source: Adopted from (Aldwaik & Pontius, 2013, 2012).

$$S_t = \frac{\text{Change duration } (Y_t, Y_{t+1})}{(\text{duration of } [Y_t, Y_{t+1}]) (\text{extent size})} 100\% = \frac{\sum_{j=1}^J [(\sum_{i=1}^J C_{tij}) - C_{tjj}]}{(Y_{t+1} - Y_t) (\sum_{j=1}^J \sum_{i=1}^J C_{tij})} 100\% \quad (5.3)$$

$$L_{ti} = \frac{\text{annual loss of } i \text{ during } [Y_t, Y_{t+1}]}{\text{size of } i \text{ at } Y_t} 100\% = \frac{[(\sum_{j=1}^J C_{tij}) - C_{tii}] / (Y_{t+1} - Y_t)}{\sum_{j=1}^J C_{tij}} 100\% \quad (5.4)$$

$$G_{tj} = \frac{\text{annual gain of } j \text{ during } [Y_t, Y_{t+1}]}{\text{size of } j \text{ at } Y_{t+1}} 100\% = \frac{[(\sum_{i=1}^J C_{tij}) - C_{tjj}] / (Y_{t+1} - Y_t)}{\sum_{i=1}^J C_{tij}} 100\% \quad (5.5)$$

$$R_{tin} = \frac{\text{annual transition from } i \text{ to } n \text{ during } [Y_t, Y_{t+1}]}{\text{size of } i \text{ at } Y_t} 100\% = \frac{C_{tin} / (Y_{t+1} - Y_t)}{\sum_{j=1}^J C_{tij}} 100\% \quad (5.6)$$

$$\begin{aligned} W_{tn} &= \frac{\text{annual gain of } n \text{ during } [Y_t, Y_{t+1}]}{\text{size of } non - n \text{ at } Y_t} 100\% \\ &= \frac{[(\sum_{i=1}^J C_{tin}) - C_{tnn}] / (Y_{t+1} - Y_t)}{\sum_{j=1}^J [(\sum_{i=1}^J C_{tij}) - C_{tnj}]} 100\% \end{aligned} \quad (5.7)$$

5.5 Land use land cover change projection

5.5.1 Markov Cellular Automata Analysis

The land use land cover projection for this study was projected based on the Markov Chain process. The Markov Chain Analysis (MCA) is an aggregate, macroscopic, stochastic, modeling process that can be used for predicting future changes based on changes that occurred in the past (Bozkaya et al., 2015; Kumar et al., 2016). Given a subdivision of an area into a number of cells each representing a given type of land use land cover at a given time, the MCA calculates the probability that a cell will undergo change from one land use land cover category to another within a given period of time based on observed data between time periods (Leta et al., 2021).

The probability of changing from one state to another state is known as a transition probability. The probability that each land use land cover category can change to other categories and the

number of pixels that are expected to change is calculated by MCA generating what is call the transition matrix. A Markov transition matrix P can be expressed as in Equation 5.8

$$P = P_{ij} = \begin{bmatrix} P_{i1} & P_{i2} \dots & P_{in} \\ \vdots & \ddots & \vdots \\ P_{n1} & \dots & P_{nn} \end{bmatrix} \quad (5.8)$$

Where: $0 \leq P_{ij} \leq 1, \sum_{j=1}^n P_{ij} = 1, i, j = 1, 2, 3 \dots n$

P = the Markov transition matrix P_i , j = the land use and land cover category of the first time period and second time period P_{ij} = the probability of changing from land use category i to land use and land cover category j . The outcome is a set of conditional probability images or transitional potential maps which reports the probability that each land use land cover category would be found at each pixel after the given number of time units (Leta et al., 2021). The problem with Markov analysis is that it does not consider the causes of land use land cover change let alone being insensitive to (geography) space and provides. This weakens of Markova is addressed by adding the spatial element to the modeling process using Cellular Automata (CA) (Bozkaya et al., 2015; Kumar et al., 2016; Leta et al., 2021).

A CA may be considered as a discrete dynamical system that models the complex behavior based on simple, logical rules, for animating cells on a lattice. CA represents space by a uniform 'n' dimensional grid of cells (e.g., $n=1, n=2$), with each cell carrying some data. The basic computational unit in CA is called a 'cell' and such cells are usually nonlinear dynamic systems. The neighborhood is a concept representing the set of cells that will be directly interacting with the centrally located cell considered. In the CA system, the space was represented by a grid, time by uniform steps, and the states within the system were finite, integer numbers (Kumar et al., 2016). The CA system consisted of four elements namely, 1. Cells, 2. States, 3. Neighborhoods and 4. Rules. Cells were the smallest of spatial units. States are attributes of the cells for a given time step. Relationships among the cells were defined within their neighborhoods. The next state of each cell was determined by the states of its neighboring cells. Rules are used to define the states of the cells in the next time step.

Future land use land cover change was predicted using Cellular Automata and Markov chain based built in module called CA_- available within the TerrSet software. CA-Markov is a combined Cellular Automata/Markov Chain/Multi-Criteria/Multi-Objective Land Allocation (MOLA) land use land cover prediction model. CA-Markov adds an element of spatial contiguity as well as knowledge of the likely spatial distribution of transitions to Markov chain analysis. The algorithm works as follows: The transition areas file from a Markov Chain analysis of two prior land use and land cover maps establishes the quantity of expected land use land cover change from each existing category to each other category in the next time period. The later land use land cover image used for the Markov Chain analysis is used as the starting point for change simulation. Suitability maps or transition potential maps for each land use land cover establish the intrinsic suitability of each pixel for each land use land cover type. However, a contiguity filter normally down-weights the suitability of pixels far from existing areas of that class (as of that iteration), thus giving preference to contiguous suitable areas (Leta et al., 2021; Kumar et al., 2016).

The number of iterations chosen establishes the number of time steps that will be used for the simulation. Within each time step, each land cover is considered in turn as a host category and all other land use land cover classes will act as claimant classes and compete for land (only within the host class) using the multi-objective land allocation (MOLA) procedure (Kumar et al., 2016). The area requirements for each claimant class within each host are equal to the total established by the transition area's file divided by the number of iterations. The results of each MOLA operation are overlaid to produce a new land cover map at the end of each iteration. The filter is integral with the action of the Cellular Automata component. Its purpose is to down-weight the suitability of pixels that are distant from existing instances of the land use and land cover type under consideration. To be a likely choice for land use land cover conversion, the pixel must be both inherently suitable and near to existing areas of that class (Kumar et al., 2016). The default 5x5 filter has the following kernel shown in the (Table 5.5).

Table 5.5: Filter for land use land cover iterations adopted from (Kumar et al., 2016)

0	0	1	0	0
0	1	1	1	0
1	1	1	1	1
0	1	1	1	0
0	0	1	0	0

Cellular Automata Markov automatically normalizes the filter kernel to force the values to add up to 1. This filter is passed over a Boolean image for each class from the current land use land cover image within each iteration. These are multiplied by the original suitability maps to down-weight suitability distant from existing areas of each class. The results are then stretched back to a byte (0-255) range. The down-weighted suitabilities never exceed 90 % of their original value. This ensures that suitable areas can be found if none are available in proximate areas.

5.6 Results

5.6.1 Accuracy of classification and transitions of land use land cover

The accuracy of the classification was assessed using a 7 x 7 confusion matrix (Table 5.6). Results indicate that overall accuracy of classification for the 2016 image was 85 % and the Kappa coefficient was 0.85 respectively. The minimum threshold accuracy of land use land cover classification set by Anderson et al., (1976) is 85 %, therefore the classification in the current study met the requirement. According to Moriasi et al., (2007), if 0.7 is less than Kappa which is less than 0.85, the classification is considered very good. For this study, Kappa was found to be 0.85 hence, the classification was very good.

Table 5.6 : Confusion transition matrix for 2016 land use land cover class

		Predictor							Total	Users' Accuracy (%)
		Agricultural land	Bare land	Built-up areas	Forests	Grasslands	Wetlands	Woodlands		
Ground truth	Agricultural land	20	0	1	0	1	5	1	28	71
	Bare lands	0	11	0	0	0	0	3	14	79
	Built-up areas	0	0	3	0	0	0	0	3	100
	Forests	0	1	0	33	0	0	0	34	97
	Grasslands	1	0	0	0	16	0	0	17	94
	Wetlands	0	0	0	0	0	15	0	15	100
	Woodlands	1	1	0	2	0	0	2	6	33
Total		22	13	4	35	18	20	6	118	
Producers' Accuracy (%)		91	85	75	94	89	75	33		

5.6.2 Magnitudes of land use land cover in Sironko catchment between 1986 and 2016

The magnitudes of land use and land cover categories in Sironko catchment in 1986, 2000, 2016 and 2040 are presented in (Figure 5.1). The results show that the most dominant land use land cover categories in Sironko catchment are agricultural land, grasslands, wetlands, forests, and woodlands. However, agricultural land consistently reduced from 38.71 % of the total catchment area in 1986 to 35.81 % in 2000, and further to 31.21 % in 2016, respectively. Forests meanwhile reduced from 12.50 % of the total catchment area in 1986 to 8.43 % in 2000 as a result of encroachment before recording a sharp increase to 15.52 % in 2016 possibly due to conservation efforts. Likewise, wetlands reduced from 26.02 % of the total catchment area in 1986 to 20.77 %

in 2000 after which it slightly recovered to 21.96 % in 2016. In the case of woodlands, it increased from 5.75 % in 1986 to 12.35 % in 2000 where it then decreased to 7.10 % in 2016. Grasslands on the other hand, increased from 16.65 % in 1986 to 21.40 % in 2000, and further to 23.13 % in 2016, respectively.

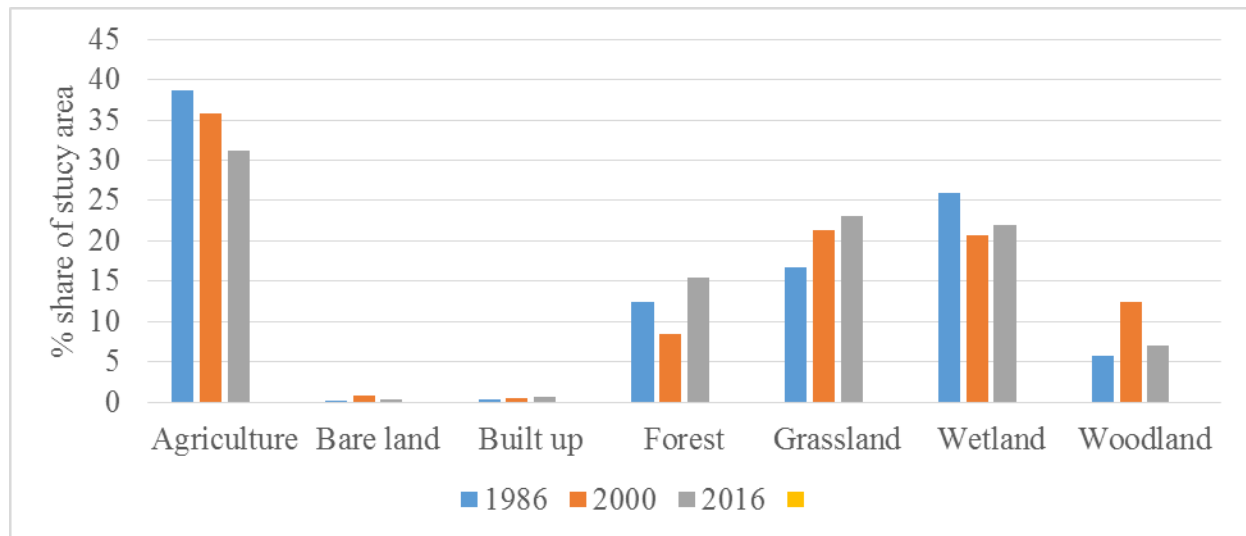


Figure 5.1: Magnitudes of land use land cover in Sironko catchment from 1986 to 2016

5.6.3 Gains or loss in land use land cover between 1986 and 2016

Results in Table 5.7 show that agricultural land reduced from 1520 km² in 1986 to 1406 km² in 2000 and further to 1225 km² in 2016 corresponding to an 7 % decrease between 1986 and 2000 and 13 % between 2000 and 2016, respectively. Similarly, wetlands reduced from 1022 km² in 1986 to 816 km² in 2000 before increasing to 862 km² in 2016, which gives a 20 % decrease between 1986-2000, and a 5 % increase in the period 2000-2016. On the other hand, forests reduced from 491 in 1986 to 331 km² in 2000 but increased almost two times to 609 km² in 2016, which corresponds to a 33 % decrease between 1986 and 2000 and an increase of 84 % in the period 2000-2016. Woodlands meanwhile increased from 226 km² in 1986 to 485 km² in 2000 before reducing to 279 km² in 2016 corresponding to 115 % increase between 1986 and 2000 and 42 % decrease in the period 2000-2016. Similarly, grasslands increased from 654 km² in 1986 to 840 km² in 2000 and finally to 908 km² in 2016 representing a 39 % increase between 1986 and 2000 and a further 8 % increase between 2000 and 2016, respectively. Built up areas increased from 13 km² in 1986 to 18 km² in 2000 and to 40 km² in 2016 corresponding to a 40 %

increase between 1986-2000 and 57 % increase between 2000 and 2016, respectively. Bare land constituted a very small portion of the total catchment and its trend can be seen in (Table 5.7).

Table 5.7: Gains or loss in land use land cover between 1986 and 2016

Land use land cover type	Total area coverage in (km ²)			Gain or loss (%) between different times		
	1986	2000	2016	1986-2000	2000-2016	1986-2016
Agricultural land	1520	1406	1226	-7	-13	-19
Bare land	2	31	15	1541	-53	666
Built-up areas	13	18	28	40	57	120
Forests	491	331	609	-33	84	24
Grasslands	654	840	908	29	8	39
Wetlands	1022	816	862	-20	6	-16
Woodlands	226	485	279	115	-42	23
Total	3927	3927	3927	-	-	-

Critical analysis revealed that between 1986 and 2000 forests recorded net loss while woodlands and grassland recorded net gains and the post persisted land use land cover types for this period were agricultural lands, wetlands and grasslands (Figure 5.2).

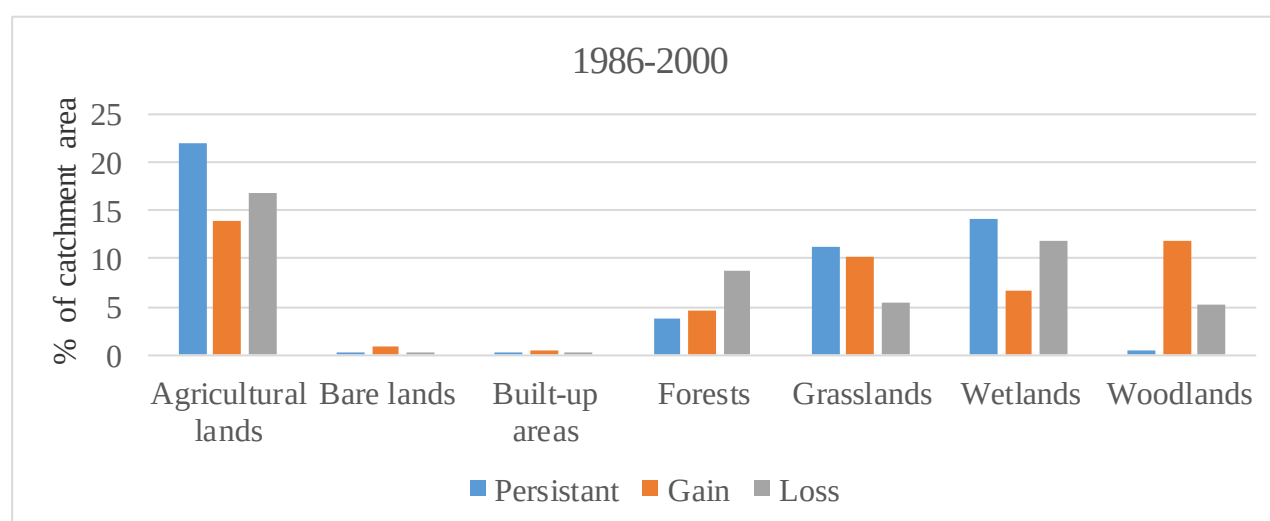


Figure 5.2: Land use land cover change between 1986 and 2000

For the period 2000-2016 meanwhile, agricultural land and woodlands recorded net losses whereas forests, grasslands and wetlands registered net gains and bare lands and built-up areas remained almost statics just like in the first interval (Figure 5.3). The categories that persisted the most between 2000 and 2016 were agricultural lands, grasslands, and wetlands respectively.

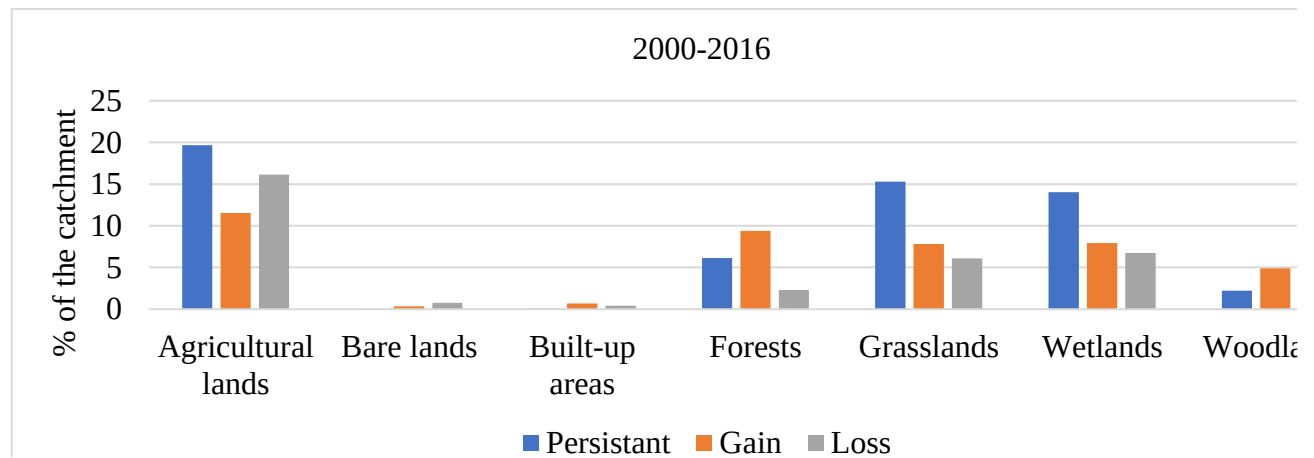


Figure 5.3: Land use land cover change between 2000 and 2016

5.6.4 Land use land cover change intensity for the period 1986-2000 and 2000-2016

Category level intensities compares the gains and losses of categories to the overall intensity of change in the entire study area (uniform intensity), indicated by the dotted horizontal line (Figure 5.4). If a category's gain or loss extends above the uniform intensity line, the gain/loss is active, otherwise it is dormant. Accordingly, between 1986 and 2000, bare lands, built-up areas, grasslands and woodlands were the active gainers whereas forests were the active lesser (Figure 5.4).

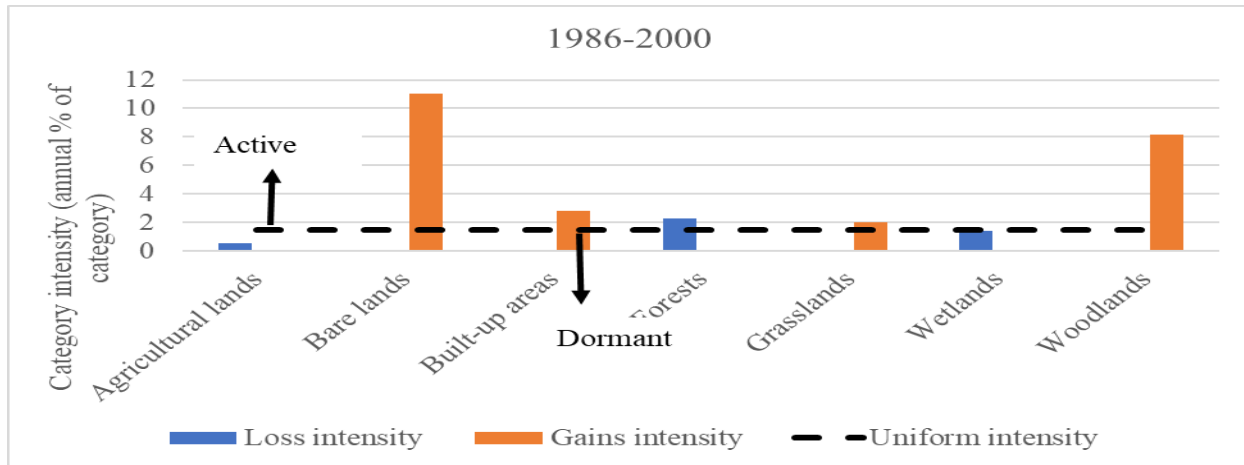


Figure 5.4: Land use and land cover category intensity between 1986 and 2000

Similarly, between 2000 and 2016, built-up areas and forests were the active gainers while agricultural lands, bare lands, and woodlands were the active losers. On the other hand, the dormant losers for this interval were agricultural lands and forests (Figure 5.5).

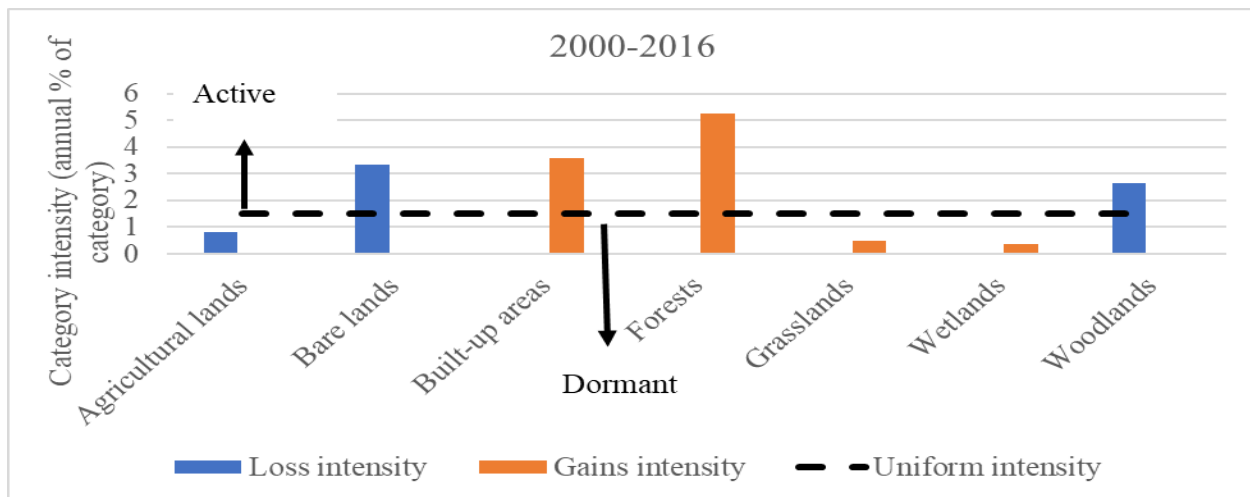


Figure 5.5: Land use and land cover category intensity between 2000 and 2016

5.6.6 Land use land cover transition intensities for the period 1986-2000 and 2000-2016

In this study, transition intensities were investigated only for agricultural lands, grasslands, wetlands, forests, and woodlands being the most dominant land use and land cover categories in Sironko catchment. It was also noted that agricultural lands expanded in built-up areas, forests,

grasslands, woodlands, and wetlands while it avoided bare lands and woodlands respectively in both the first and the second intervals (Figure 5.6)

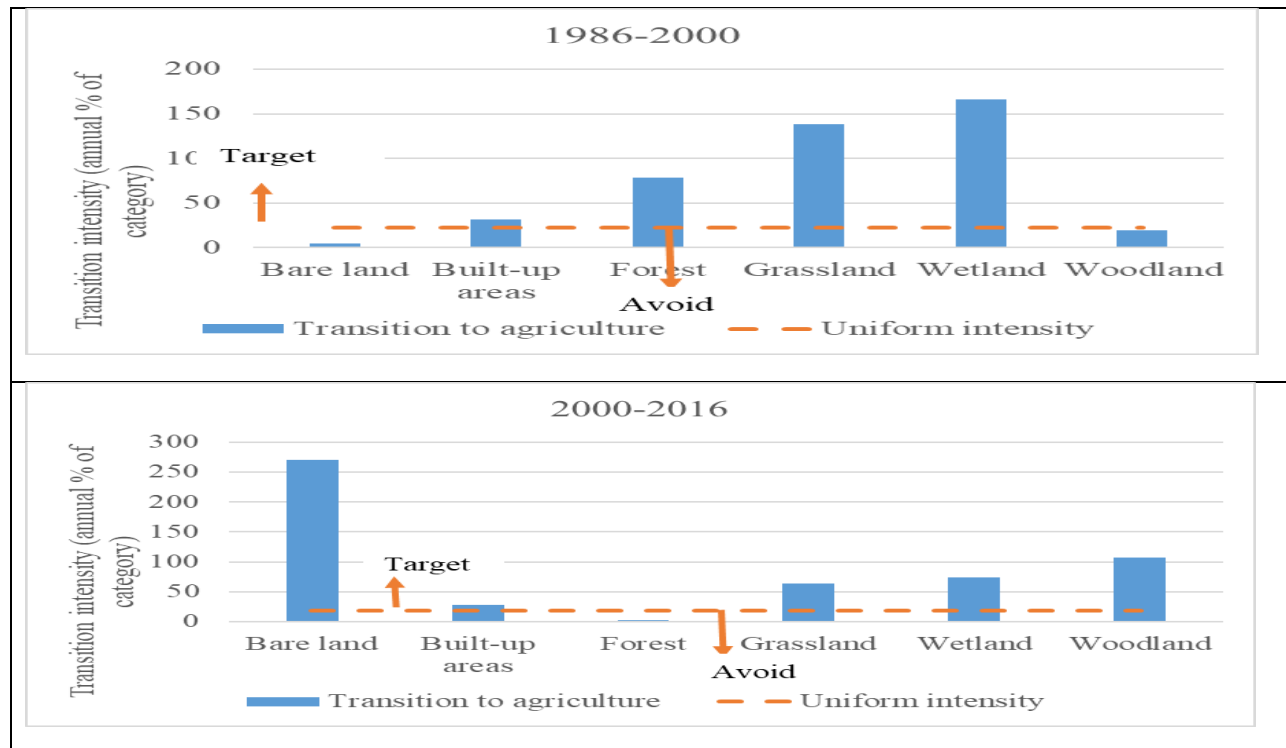


Figure 5.6: Transition to agricultural lands between 1986 and 2000 and 2000 and 2016

Figure 5.7 shows that forests targeted agricultural lands, grasslands, and wetlands but avoided bare lands, built-up areas, and forests between 1986 and 2000. Similarly, between 2000 and 2016 forests targeted only agricultural lands and woodlands but avoided all the other categories.

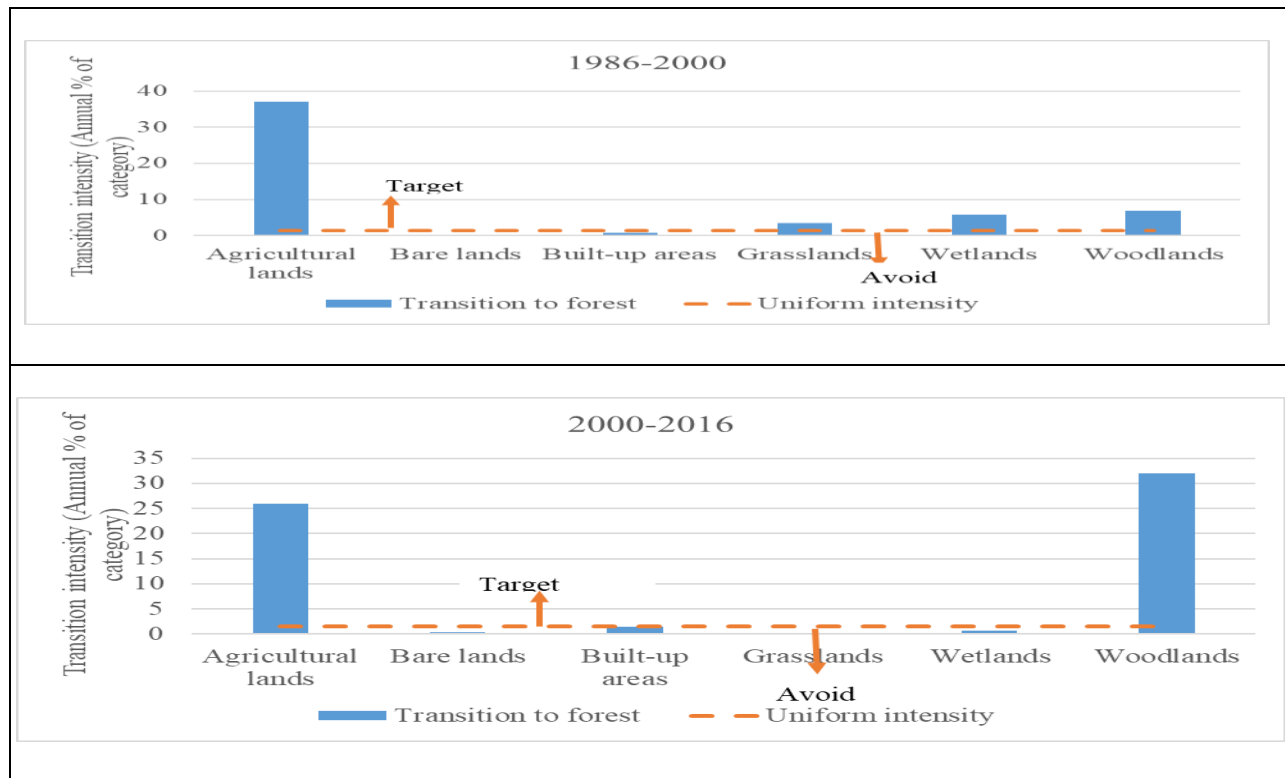


Figure 5.7: Transition intensity to forests between 1986-2000 and 2000-2016

The transition to woodland as shown in Figure 5.8 suggests that between 1986 and 2000, woodlands targeted all the other land use and land cover categories whereas in the period 2000 and 2016 it targeted bare lands, built-up areas, forests, and grasslands but avoided agricultural lands.

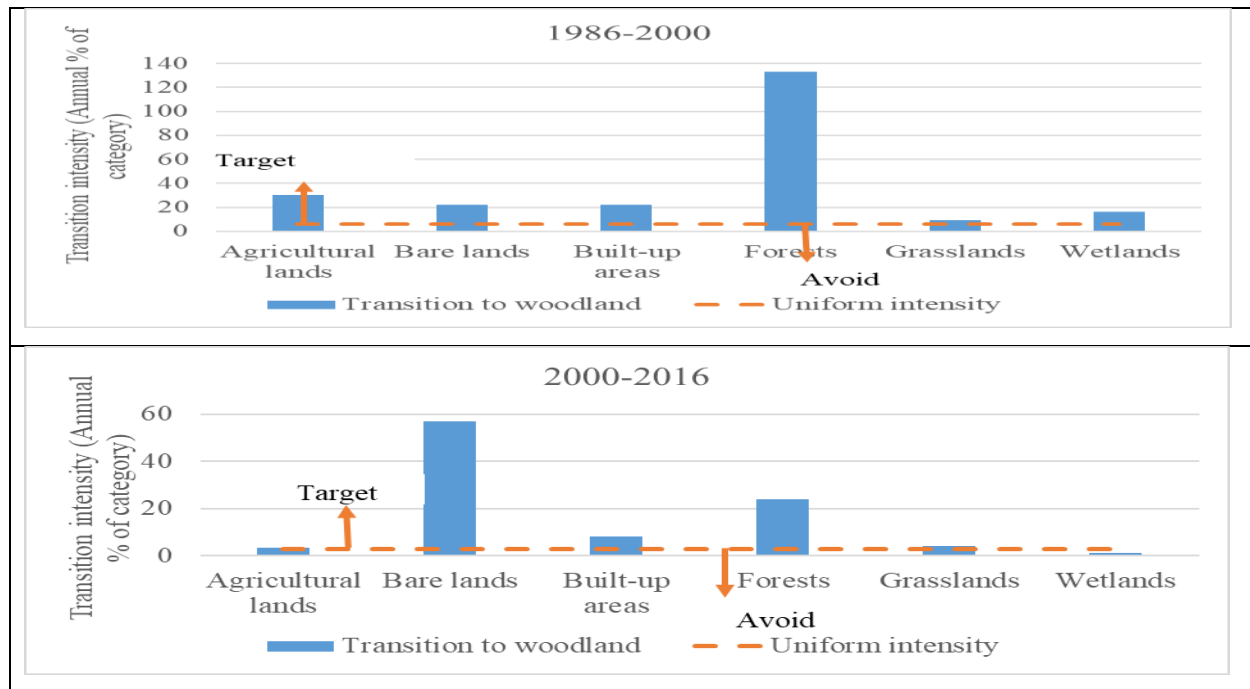


Figure 5.8: Transition to woodlands between 1986-2000 and between 2000 and 2016

Transition to wetlands on the other hand suggests that between 1986 and 2000, wetlands targeted agricultural lands, built-up areas, forests, and grasslands but avoided bare lands, and woodlands (Figure 5.9). In the same vine, between 2000 and 2016, wetlands targeted all the other land use and land cover categories except forests.

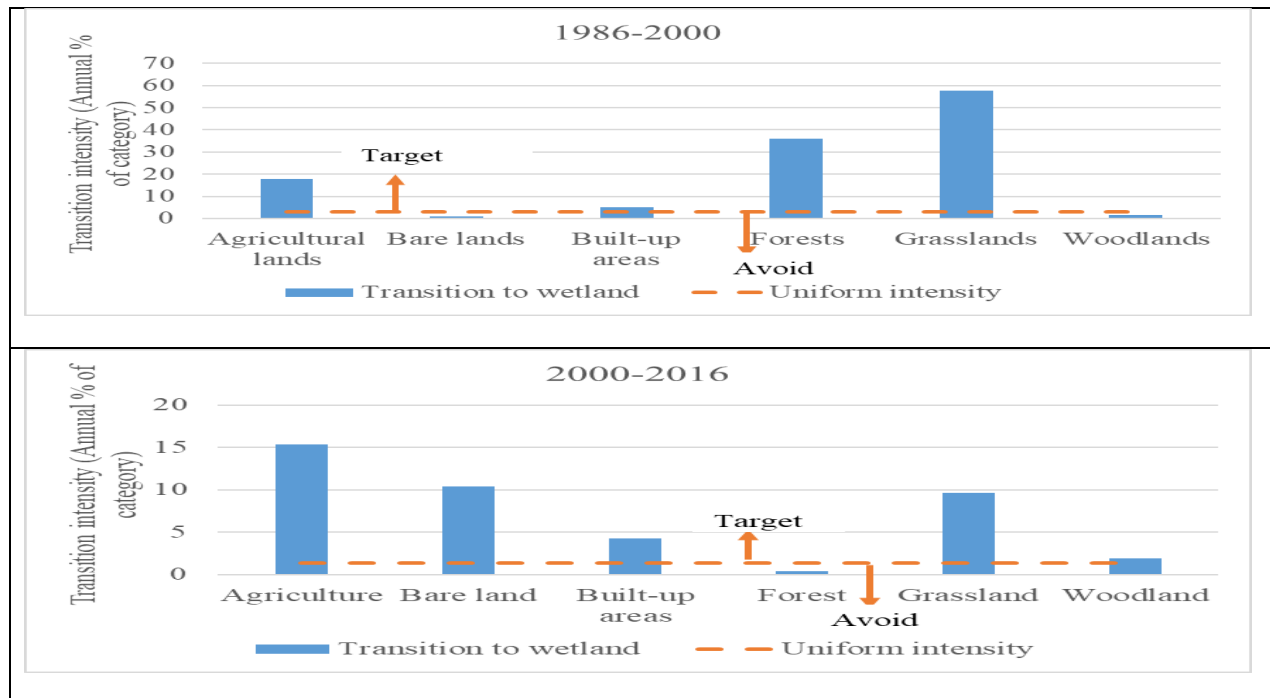


Figure 5.9: Transition to wetlands between 1986 and 2000 and between 2000 and 2016

Furthermore, transition to grasslands as illustrated in Figure 5.10 indicates that from 1986 to 2000 grasslands expansion mainly targeted woodlands and wetlands but avoided all the other land use categories. Whereas in the second interval, grasslands only targeted agricultural lands and wetlands while avoiding all the other land use and land cover categories.

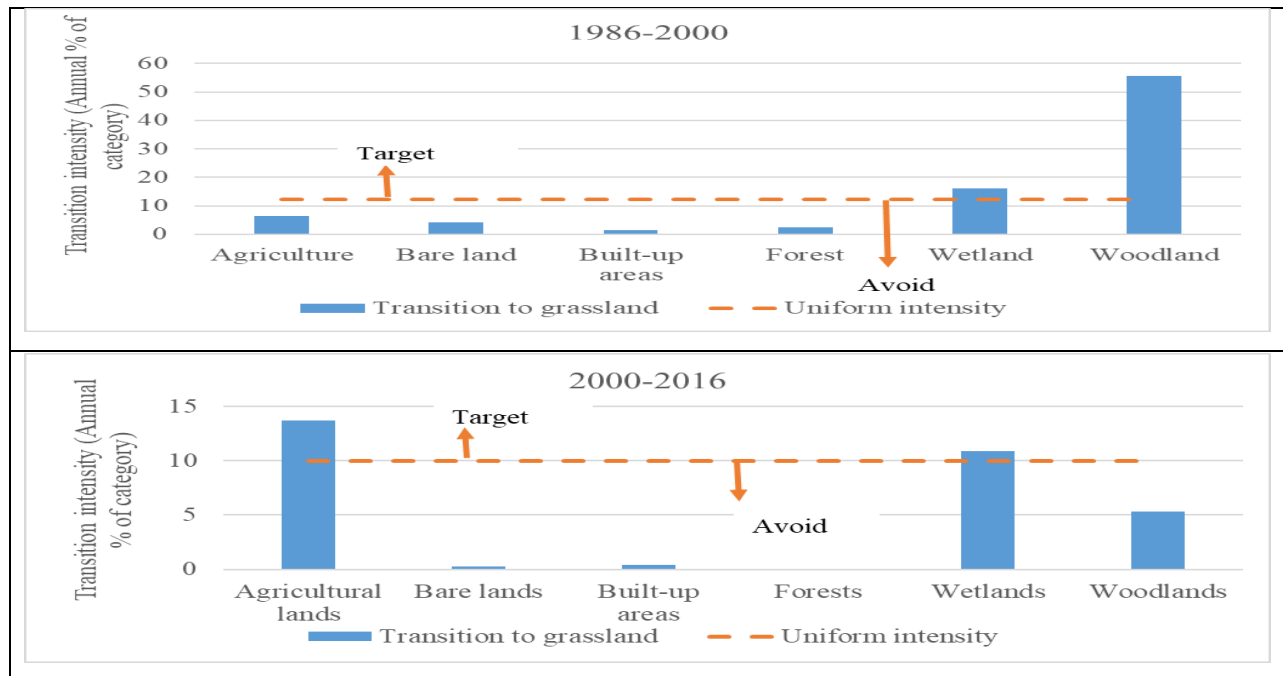


Figure 5.10 Transition to grasslands between 1986-2000 and between 2000 and 2016

5.6.7 Land use land cover dynamics between 2016 and 2040

Consideration of the driving variables/assumptions (slopes, elevation, distance to road, distance to rivers, and distance to settlement) generated transition potential sub-models with very high levels of significance (p-values) and accuracies (%) (Table 4.8). This implies that the assumption made in the LULCC prediction were valid and provide a justification for using the CA-Markov chain process to successfully predict the land use and land cover scenarios in the catchment in 2040. It is also seen from the Table that forests will significantly transitioned p-value = to agricultural lands in the future scenarios. Therefore, the Null hypothesis that forests will not significantly transition to agricultural lands in Sironko catchment in the future scenarios is rejected.

Table 5.8: Transition potential sub-models for the different land use land cover types

S/No.	Transition from-to-	Accuracy	P-values
1	Agricultural land to Built-up areas	71.94%	0.0010
2	Agricultural land to Forests	75.41%	0.0010
3	Agricultural land to Grasslands	69.28%	0.0003
4	Agricultural land to Wetlands	68.29%	0.0010
5	Agricultural to Woodlands	70.83%	0.0010
6	Forests to Agricultural	81.33%	0.0010
7	Grasslands to Agricultural	71.28%	0.0001
8	Grasslands to Wetlands	51.28%	0.0010
9	Grasslands to Woodlands	62.15%	0.0010
10	Wetlands to Agricultural	61.31%	0.0003
11	Wetlands to Grasslands	66.63%	0.0001
12	Wetlands to Woodlands	59.91%	0.0010
13	Woodlands to Agricultural	82.82%	0.0003
14	Woodlands to Grasslands	68.87%	0.0010
15	Woodlands to Wetlands	62.74%	0.0005

As seen from Table 5.9, agricultural land is projected to increase by 58.9 km², built-up areas by about 21 km², and grasslands 16 km² respectively between 2016 and 2040. On the other hand, wetland is projected to decrease by 74.1 km², woodlands by 19 km² whereas, forests and bare lands will remain nearly unchanged. The projected small increase in forests will mainly come from new plantations based on the assumption that protected area (natural forests) boundary is not going to change.

Table 5.9 Land use land cover dynamics between 2016 and 2040

Land use and land cover type	Km² in 2016	Km² in 2040	Change Km²	% Change
Agricultural lands	1225.66	1282.58	56.92	05
Bare lands	14.56	14.58	0.02	00
Built up areas	27.85	48.53	20.68	74
Forests	609.33	608.92	-0.41	00
Grasslands	908.44	924.32	15.88	02
Wetlands	862.37	788.29	-74.08	-09
Woodlands	278.85	259.85	-19	-07

5.6.8 Patterns of land use land cover in Sironko catchment between 1986 and 2040

The spatial distributions of the different land use and cover categories in the Sironko catchment in 1986 and 2000 and 2016 and 2040 are shown in Figure 5.11 and 5.12 respectively. The maps indicate that woodlands were more abundant in the north-eastern part of the study area in 1986 but kept on reducing in 2000, 2016, and 2040 respectively. Similarly, agricultural lands extend from the west, to central, and to the eastern part of the watershed in all the years under investigation. Built-up areas were mostly in areas where there is agricultural land between 1986 and 2016 and will continue to do so in 2040. Forests occupied the upper slope of the study area while the lowland part of the catchment mainly consists of wetlands for the entire study period.

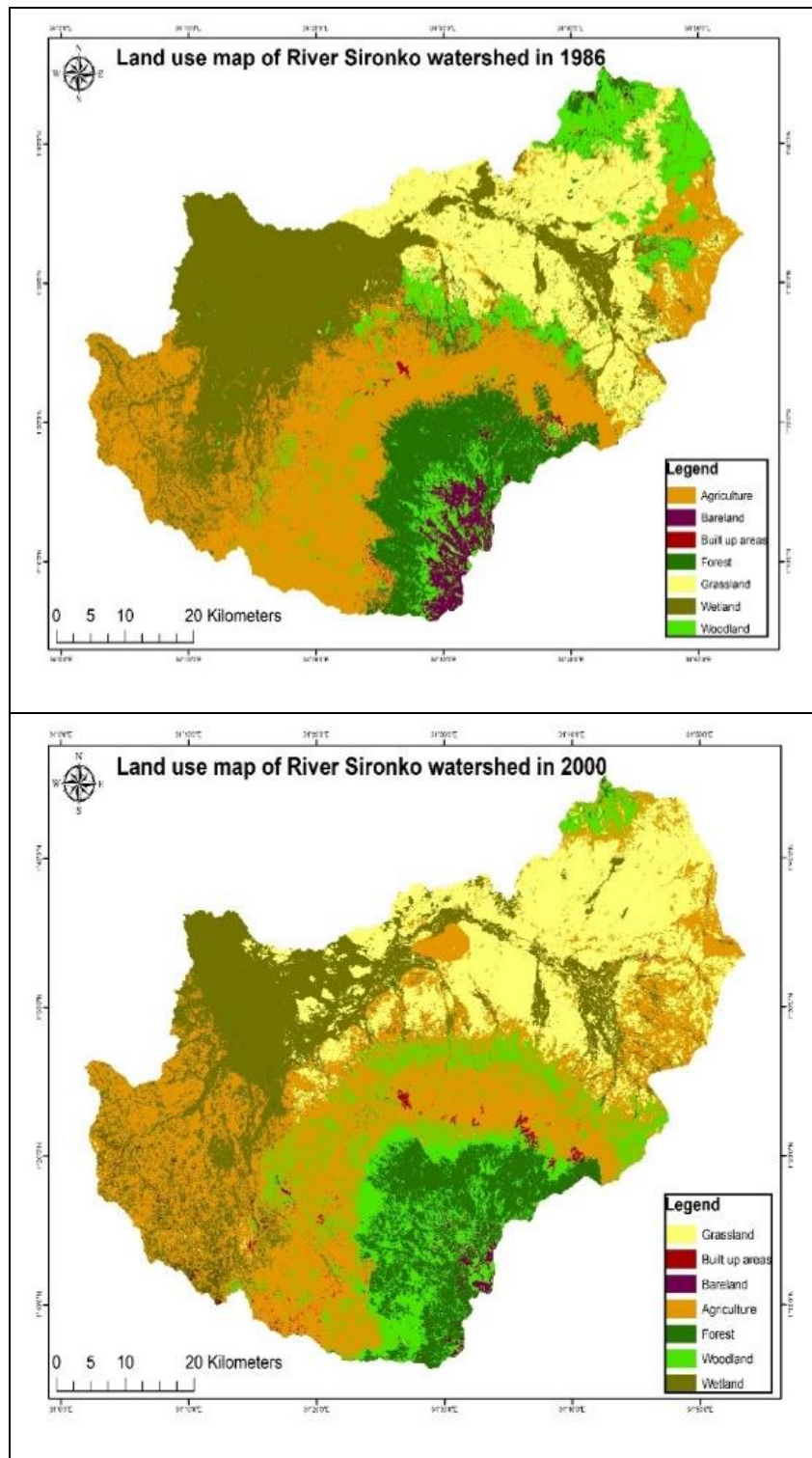


Figure 5.11 The patterns of land use land cover in Sironko catchment in 1986 and 2000

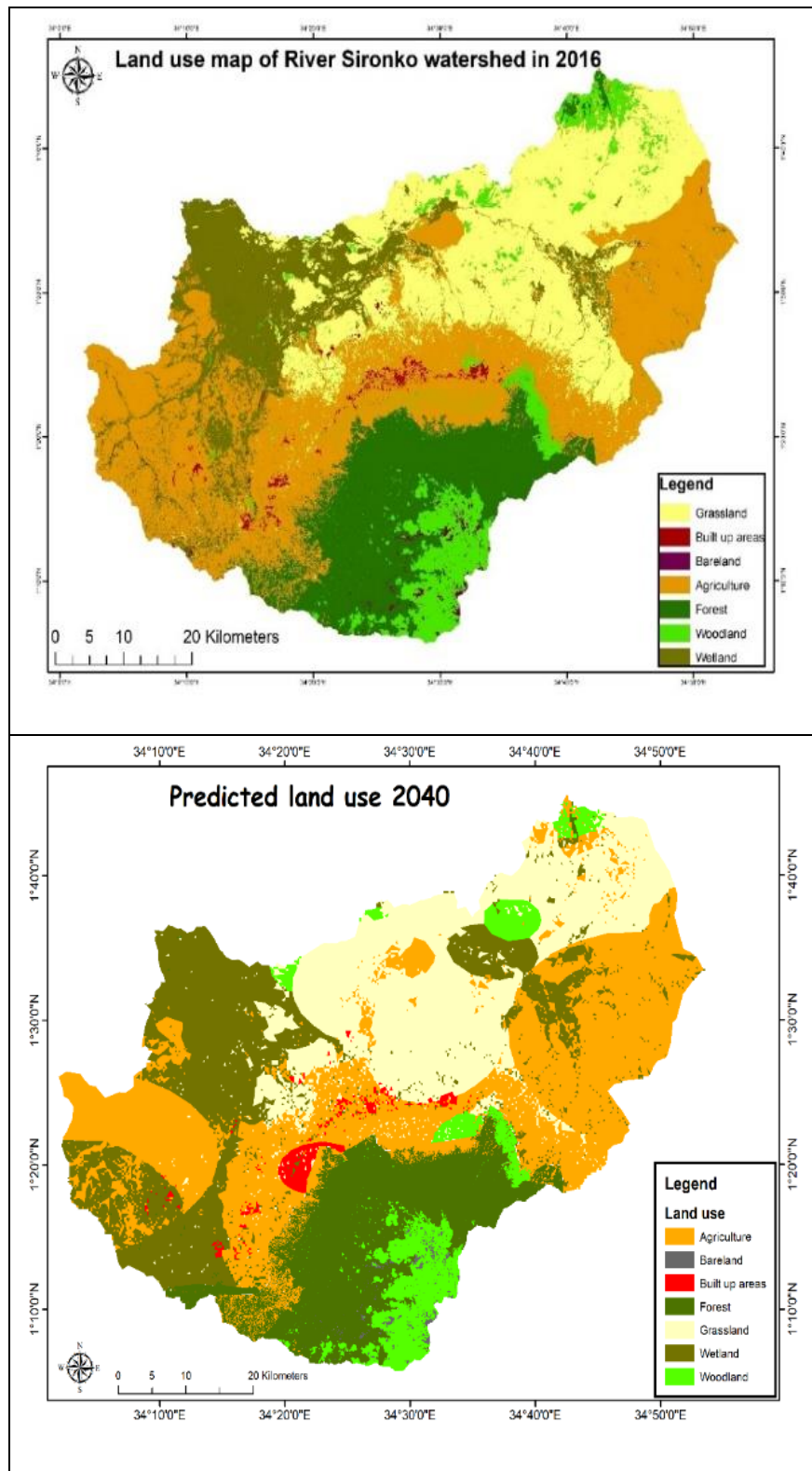


Figure 5.12 The patterns of land use land cover in Sironko catchment in 2016 and 2040

5.7 Discussion of results

5.7.1 Magnitudes of land use land cover in Sironko catchment between 1986 and 2016

The most dominant land use and land cover categories in Sironko catchment for the study period has been identified as agricultural lands, grasslands, wetlands, forests, and woodlands respectively. However, agricultural land consistently reduced in proportion throughout the study intervals due to lack of rooms for expansion in the catchment and it explains the persistence of agricultural lands (not less than 20 % of total catchment area) in both intervals. Land scarcity in the greater Mt. Elgon has been previously reported (Mugagga & Buyinza, 2013; Buyinza & Mugagga, 2010). The trend could also reflect economic growth and changing life styles of the youth who are supposed to be a big source of labour in subsistence farming. The entire Mt. Elgon region is predominantly under subsistence farming (UBOS, 2016). However, most youths are now turning away from agriculture (which is perceived as less rewarding) to sport betting, alcoholism, and motorbikes' riding (Bitanibirwe & Ssewanyana, 2021; Nabifo et al., 2021). In general terms, deforestation and wetland degradation occurred in Sironko catchment 1986-2000 whereas forests and wetlands recovery were recorded between 2000 to 2016 in the catchment. The finding is in agreement with that of Mugagga et al., (2015) and Mugagga et al., (2012), who reported decrease in forest in Mt. Elgon region between 1995 and 2013 and between 1995 and 2006, respectively. According to MWE, (2019) national wetlands coverage have reduced from 15.5 % in 1994 to 8.9 % in the year 2018/2019 and the year 2018/2019 also show 73414 ha of degraded wetlands restored.

Reflecting on Buyinza & Mugagga, (2010), the observed deforestation and wetlands reduction between 1986 and 2000 could broadly be linked to population pressure, land shortages, lack of policy implementation, land tenure systems, encroachment, and unclear park boundary around Mt. Elgon. Similarly, the recovery of wetlands and forests, and the decline in agricultural lands between 2000 and 2016 was because of conservation efforts implemented in the Mt. Elgon region. Some of the conservation efforts include: 1) the forest restoration programme 1995 by the Uganda Wildlife Authority (UWA), Ditiro et al, (2008); 2) the involuntary eviction of communities from the conservation area implemented to restore some 25,000 ha forests that had been occupied and encroached upon during the 1970s and 1980s Cavanagh & Benjaminsen,

(2014); and 3) the carbon offset project launched in Mt. Elgon areas in 1993 between UWA and a Dutch NGO, 'Face the Future' among others (Cavanagh & Benjaminsen, 2014).

5.7.2 Land use land cover intensities

Although, agricultural lands constituted the largest share of the study area over the study period, it also decreased over the entire period. In fact, agricultural lands were an active loser during the first interval and a dormant loser in second interval. This trend contradicts the national trends observed by Majaliwa et al., (2018) and Li et al., (2016) but most specifically Mugagga et al., (2012) who reported that agricultural lands increased between 1995-2000 in the neighbouring Manafa District in the Mt. Elgon region. It is also likely that some areas that were under agricultural lands have been classified as grasslands or bare lands since the images used in this study were for dry months when most agricultural fields are without crops. This could as well explain why bare lands was an active gainer in both intervals while grasslands was an active gainer in the first interval but change to a dormant loser in the second interval. The finding of this study however, agrees with the study of Mugagga et al., (2015) who reported that agricultural lands reduced from 2083 km² in 1995 to 1623 km² in 2013, equivalent to a 43% decrease between 1995-2013.

Built-up areas actively gained in both intervals and this is explained by increased population and economic growth. More people and high growth in economy meant more housing built to accommodate and provide social services like schools, hospitals, markets, roads, industries to mention but a few to the increased population. According to the National Housing and Population Census Report (UBOS, 2016) the Mt. Elgon region in Uganda is one of the most densely populated and rapidly urbanizing rural part of Uganda. On a national scale the population was 36.4 million in 2014, growing at above 3.03 % per annum, and is projected to reach 80 million by 2040 (UNFPA, 2017; UBOS, 2016). Looking at the population density, Uganda had only 48 person/km² in 1968 but this has since grown over the years to 174 persons/km² in 2014 (UBOS 2016). Uganda's economic growth has also doubled from USD 350 in the 1980s to USD 788 in 2017 and the country has attained steady economic growth at an average of 6.4 % since 2002 (UBOS, 2016; UNFPA, 2017). In the 1960-1980s, there were few numbers of people per square kilometers and with less impacts on land use land cover change. However, as the population density grow on fixed land and coupled with economic growth as

reported by UBOS (2016), there effects on land use land cover change also became pronounced as discussed above.

Forests meanwhile was an active loser between 1986-2000 but bounced back to an active gainer between 2000-2016. Mugagga et al., (2015) and Mugagga et al., (2012), also reported decrease in forest in Mt. Elgon region between 1995-2013 and 1995-2006 respectively. However, the active loss in forests between 1986-2000 and active gained between 2000-2016 could be due to conversion to agricultural lands and woodlands and vis-vas. Likewise, the trend in forests is the true opposite of woodlands trend. Woodlands was an active gainer in 1986-2000 but became an active loser between 2000-2016. Therefore, it indicates that part of forests degraded in the years before 1986 as a result of encroachments were recovering between 1986-2000 and together with planted woodlots, contributed to active gain in woodlands between 1986-2000. Between 2000-2016, most of the degraded forests had fully regenerated hence, leading to active gain in forests and active loss in woodlands between 2000-2016.

5.7.3 Land use land cover transitions

The transition to the most dominant land use and land cover categories: agricultural lands, wetlands, grasslands, forests and woodlands were investigated under section 4.3.5. It was found that agricultural lands expanded in built-up areas, forests, grasslands, woodlands, and wetlands while it avoided bare lands and woodlands respectively in both the first and the second intervals. This dynamic could be attributed to increasing population pressure (UBOS, 2016). The persistence of agricultural lands indicates that the available land for agricultural activities have been used intensively without giving it time to fallow. According to Mugagga & Buyinza, (2013); Buyinza & Mugagga, (2010), the agricultural resources based of the Mt. Elgon region has been both shrinking and degrading. Part of the land was also being converted to built-up areas to house the increasing population. With increasing population pressure, even marginal lands including steep slopes have continually been brought under cultivation (Buyinza & Mugagga, 2010).

5.7.4 Projected land use land cover change between 2016 and 2040

Between 2016-2040, there will be an increase in agricultural lands, built-up areas, and grasslands respectively. On the other hand, wetlands and woodlands will reduce while forests and bare lands will remain nearly unchanged. The projected small increase in forests will mainly come from new plantations. The assumption here is that protected area (natural forests) boundary is not going to change. In general, the result of the 2016-2040 land use land cover changes in Sironko catchment may appear not to propose any worrisome change for the future of the catchment landscapes. However, the fragile nature of the ecosystem in the Mt. Elgon region, are some points that deserve attention in terms of landscape management. The Mt. Elgon region is also prone to hazards such as soil erosion, landslides, floods, and drought (Knapen et al., 2006). Additionally, the National Housing and Population Census Report UBOS, (2016) revealed that Mt. Elgon region is one of the poorest and most densely populated, and rapidly urbanizing rural part of Uganda. The socioeconomic and demographic status of the people around Mt. Elgon force them to encroach on protected areas and forest reserves on the mountain, cultivate ecologically fragile areas such as steep slopes, swamps, and riverbanks (Nakileza et al., 2017). According to Mugagga & Buyinza, (2013); Buyinza & Mugagga, (2010) the agricultural resources base of the Mt. Elgon region has been both shrinking and degrading. With increasing population pressure, even marginal lands including steep slopes have continually been brought under cultivation (Buyinza & Mugagga, 2010). This situation may exacerbated in the future by the rapid population growth at 3.03 % per annum, and projected to increase from 34.6 million in 2014 to 80 million by 2040 (UNFPA, 2017; UBOS, 2016). Therefore, even the slightest change indicated by the model for 2040 can make a significant impact on the ecological integrity of Sironko catchment.

5.7.5 Patterns of land use land cover in Sironko catchment between 1986 and 2040

The spatial distributions of the various land use land cover types in Sironko catchment for the study period is are presented in Figure 5.11 and 5.12 respectively. The results showed that woodlands mostly occupied the slopes of Mt. Elgon and the north eastern part of the catchment. In the slopes of Mt. Elgon, the dynamic is explained by forests encroachments. In the 1980's through to the late 1990's, the north eastern part of the catchment was dominated by nomadic

pastoralism (ACTED, 2016) and little crop farming practiced (Nannyonjo, 2006). Insecurity, in the area in the 1990's and 2000's fuelled loss of livestock through raids (ACTED, 2016). The loss of livestock and forceful disarmament between 2000-2007 forced many Karamojong's youths, women and, children to migrate to neighbouring districts and even to the capital Kampala (Stites et al., 2007). The situation supported the existence of woodlands and some forests in that part of the catchment during those times. However, the disarmament restored peace and the Karamojong who did not migrate had to learn new ways of survival which included settlement, farming and, charcoal business (ACTED, 2016; Stites et al., 2007; Inselman, 2003). This resulted into most woodlands and forests in the north-eastern part of the catchment to be converted to grasslands and agricultural lands by 2016. The spatial patterns of agricultural lands and built-up areas are due to the fertile soils at the foot of the mountain. Most rural settlements are influenced by availability of land for agriculture, access to services such as schools, hospitals etc. Forests however dominated the upper slope of Mt. Elgon because it largely falls within the protected areas. The location of the wetlands in this study area was expected because naturally wetlands are found in the low land.

5.8.1 Conclusions

This study determined the dynamics of land use and land cover in the recent past and projected the current to near future land use and land cover in Sironko catchment. Remote sensed data for 1986, 2000 and 2016 were used to produce the land use and land cover maps for the respective years while intensity analysis was applied to reveal the land use and land cover dynamics. Future LULCC in the catchment was predicted in 2040 using the LCM of the TerrSet by Markov process. Based on the results, the study concludes that:

1. Although agricultural lands reduced between 1986-2016, it remained the most dominant land use and land cover type in Sironko catchment in that period and it will be between 2016-2040.
2. The period 1986-2000 was marked by deforestation and reduction in wetland area while the period 2000-2016 was dominated by forests and wetlands recovery at the expense of woodlands, agricultural lands, and bare lands.
3. Forests mainly got converted to agricultural lands and woodlands while wetlands mainly transitioned to agricultural lands, grasslands and woodlands respectively.

4. Prediction in 2040 indicates continued increase in built-up areas and that agricultural lands will also increase at the expense of wetlands and woodlands.

5.8.2 Recommendations

1. Deliberate policies intervention implemented through public-private partnership with full communities' engagement in environmental conservation while offering diversified livelihoods opportunities could accelerate community transformation, minimize deforestation and wetlands degradation in Sironko catchment.
2. Given the sensitive nature of the ecosystems in Sironko catchment, land resources management in the catchment and Mt. Elgon region should not only focus on the landscape composition but also pay attention to landscape configuration and livelihoods means of the local people.

CHAPTER SIX: TRENDS AND MAGNITUDE OF CLIMATE VARIABILITY AND CHANGE IN SIRONKO CATCHMENT ON A MEDIUM TIMESCALE

6.1 Abstract

Sironko catchment on Mt. Elgon is a water tower and food basket to millions of people. However, the main source of livelihood of the people is rain-fed agriculture which is sensitive to climate variability and change. Therefore, this study assessed the trends and magnitude of climate variability and change on a medium timescale in Sironko catchment for the sustainability of livelihoods. Baseline 1980-2009 climate data for three virtual stations Buginyanya, Kumi and Nakapiripirit were obtained from the Modern Era-Retrospective Analysis for Research and Applications (MERRA). The near future 2025-2040 climate was downscaled from the 29 GCMs of the IPCC Fifth Coupled Model Inter comparison Project (CMIP5) using delta method of the AgMIP. Five climate regimes Cool-wet, Cool-dry, Hot-wet, Hot-dry, and Middle under two Representative Concentration Pathways (RCP) 4.5 and RCP8.5, were selected using the representative temperature and precipitation sub-setting approach. Data analysis was carried out at the individual stations' level. Four seasons December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); and September, October, November (SON) was adopted. Descriptive statistics were performed in Microsoft excel 2016 while p-values of trends were generated by linear regression. Trends and trend magnitudes were determined using the Mann–Kendall trend test and Sen's slope estimator. Result shows that between 1980-2009 and 2025-2040, MAM rainfall has been/will be less variable $20 < CV$ or moderately variable $20 < CV < 30$ whereas SON rainfall has been/will be highly variable $CV > 30$ across Sironko catchment. Both increasing and decreasing trends which are not significant have been detected in seasonal rainfall in all the stations. Annual rainfall will increase at $p < 0.05$ level of significant in Kumi and Nakapiripirit stations between 2025 and 2040. Mean temperature increase increases at $p < 0.05$ level of significant between 1980-2009 and 2025-2040 was detected. Temperature trends may accelerate biodegradation in River water, increase evapotranspiration, decrease soil moisture, ground water and river flow, hence compromising water quality and quantity in future.

**This chapter is based on Luwa, J. K., Majaliwa, J. M., Bamutaze, Y., Kabenge, I., Pilesjo, P., Oriangi, G., & Mukengere, E. B. (2021). Variabilities and Trends of Rainfall , Temperature , and River Flow in Sipi Sub-Catchment on the Slopes of Mt . Elgon , Uganda. Water, 13(1834), 1–18. <https://doi.org/10.3390/w13131834>*

6.2 Introduction

Climate variability and change affect agricultural production, food and water security, and ecosystems' health. Catchment scale knowledge of climate variability and change is vital for the sustainability of food and water securities as well as the livelihoods of local communities (Langat et al., 2017). For decades, climate research has revolved around a global (Guo et al., 2015), regional, and basin scales, with less emphasis on small catchments (Poortinga et al., 2017). According to Marques et al. (2015), research on climate variability and change should extend to small catchments to provide practical applications to sectors such as agriculture, water, energy, and tourism among others. In the field of hydrology, such research can provide knowledge on hydrologic forecasting (Marques et al., 2015). Moreover, agriculture extension officers can apply such knowledge in guiding farmers on when to prepare their land and when to plant which type of crops (Langat et al., 2017; Bekele et al., 2016). More still, environmentalists and other agencies can use this knowledge in early warning systems for disaster risk reduction (Fentaw et al., 2017; Onyutha, 2016).

Many scholars have investigated the variations in rainfall and river flow in the horn of Africa in the last two decades (Asfaw et al., 2018; Tigabu et al., 2018; Kassian et al., 2017; Onyutha & Willems, 2017). To illustrate these, Onyutha & Willems, (2017) studied four selected catchments of River Nile; Fentaw et al. (2017) focused on the Tekeze River Basin in Ethiopia; Tigabu et al. (2018) studied the basin of Lake Tana in Ethiopia; Kassian et al., (2017), conducted his study in the Iringa region of Tanzania; and Langat et al. (2017) focused on the Tana River Basin in Kenya. All these authors found significant variations and change in climate with serious implications on surface water resources. On the other hand, Asfaw et al. (2018) employed trend analysis to inspect changes in both intra- and inter-annual variability of rainfall and temperature in North Central Ethiopia from 1901 to 2014. Annual rainfall was found to have significantly declined in some stations while others had no significant decline. Across Ghana, Abbam et al. (2018) examined the spatiotemporal variations in rainfall and temperature and reported that Ghana's climate had become progressively drier and prone to drought conditions over the last century. Furthermore, over East Africa, Gebrechorkos et al. (2019) analyzed long-term trends in rainfall (1981–2016) and maximum and minimum temperature (T-max and T-min) (1979–2010) on seasonal and annual scales. Results showed contradicting statistically significant and non-

significant decreasing and increasing trends in rainfall and maximum temperature depending on the locations.

In Uganda, evidences of climate variability and change at different spatiotemporal scales are inconclusive and give mixed results (Mwaura & Okoboi, 2014; Diem et al., 2014; Mukasa et al., 2020). For example, the study by Mwaura & Okoboi, (2014) covered the whole country and reported that whereas it was clear the mean temperature increased insignificantly, rainfall did not show any significant increase between 1981 and 2008. In the study by Diem et al. (2014), a significant decrease in seasonal rainfall in western and central regions of Uganda was reported during 1983–2012. On the other hand, Mukasa et al. (2020) found significant decrease in the average annual rainfall, and March, April, and May (MAM); January, December, and February (JDF) seasons rainfall respectively in Kashari sub-county in Western Uganda between 1987 and 2017. But reported significant increase in average maximum and minimum temperature on both annual and seasonal scales. In other similar studies, Mubialiwo et al. (2020) reported significant increase in annual and MAM seasonal rainfall in the Mpologoma catchment in Eastern Uganda for the period 1948–2016. Meanwhile, Nsubuga et al. (2014) reported significant increase in annual and MAM seasonal rainfall in the Albert-Victoria water catchment area in Uganda for the period 1943–1977. According to literature, variability and change in climate in different parts of Uganda indicate variable results, thus underpinning the need to conduct this study at catchment level, particularly in the slopes of mount Elgon, which has witnessed increased frequencies of floods, droughts, landslides, and soil erosion since 1990.

Sironko catchment presents a diverse landscape of variable topography, discontinuous land cover types, and seasonally distinct rainfall patterns, all of which influence the distribution of rainfall at fine spatiotemporal scales Stampone et al., (2011) with serious implications on subsistence cropping systems, the sustainability of water resources, and livelihoods. However, scientific knowledge regarding the trends and magnitudes of climate variability and change in Sironko catchment is still inadequate. It is therefore highly possible that policy and management decisions in the catchment have relied upon national studies that are often too coarse to capture important variability at a finer scale, where management actions operate (Stampone et al., 2011).

This study aimed at investigating the trends and magnitude of climate variability and change on a medium timescale in Sironko catchment for the sustainability of the water resources and livelihood. As such, this objective was accomplished in two parts. Part one investigated fine-scale variability in climate and river flow in Sipi sub-catchment. Part two assessed the trends and magnitude of climate variability and change on a medium timescale in Sironko catchment.

6.3 Materials and methods

6.3.1 Study area

Part one of this objective was conducted in River Sipi sub-catchment (918 km²) Figure 5.1 of Sironko catchment (399.7 km²) on the slopes of Mt. Elgon (Figure 3.1). Detailed general description of the study area are given in chapter three section (3.1.1 and 3.1.5).

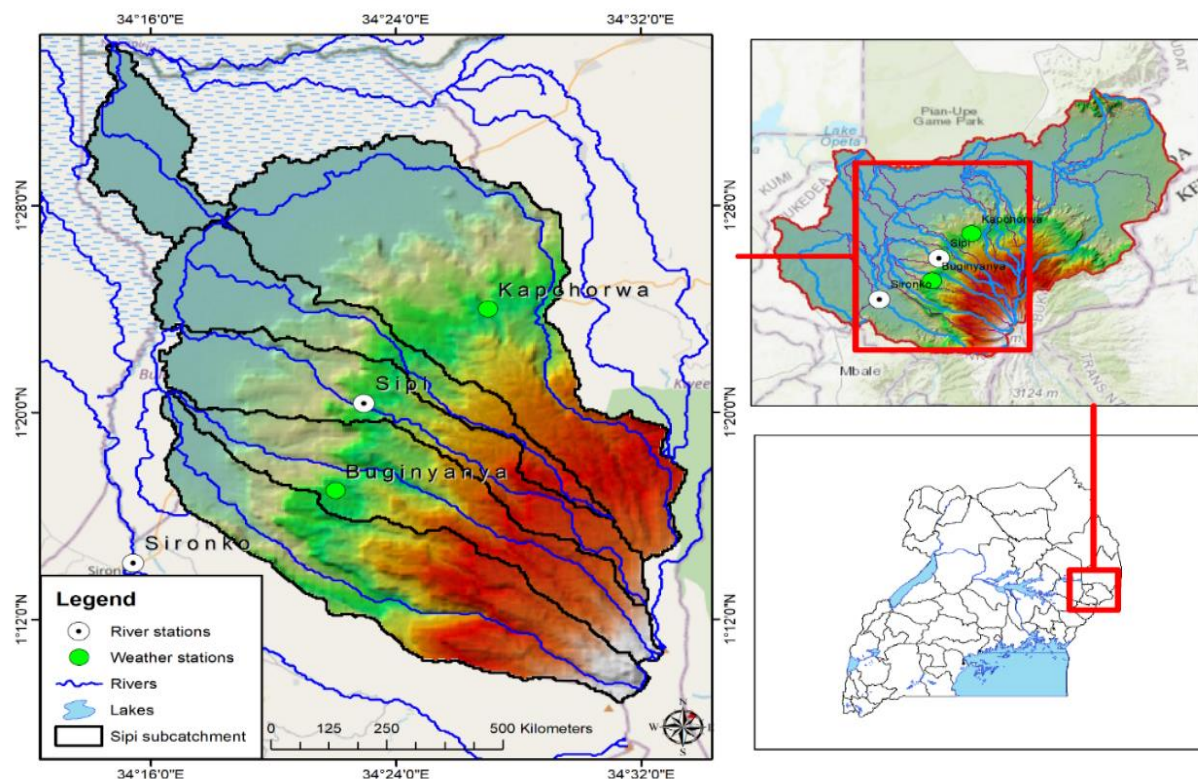


Figure 6.1: Map of Sipi sub-catchment in Sironko catchment on Mt. Elgon, Uganda.

6.3.2 Methods of data collection

Observed daily rainfall and temperature data (1981–2015) for Buginyanya and Kapchorwa weather stations were obtained from the Uganda National Meteorological Authority (UNMA), while daily river flow data for River Sipi (1998–2015) was obtained from the Ministry of Water and Environment (MWE), Kampala (Table 6.1).

Table 6.1: Location attributes climate and stream flow data

Climate Data	Altitude (m.a.s.l.)	Longitude (degrees)	Latitude (degrees)
Buginyanya	1845	34.37	1.28
Kapchorwa	1920	34.45	1.4
Sipi River gauge	1075	34.15	1.14

Note: m.a.s.l. denotes meters above sea level

Daily rainfall, temperature minimum and maximum, solar radiation, wind speed, and relative humidity data for three virtual/grid stations Buginyanya, Kumi and Nakapiripirit 1980-2010 Table 6.2 from the Modern Era-Retrospective Analysis for Research and Applications (MERRA) provided by the Agricultural Model Inter-comparison and Improvement Project (AgMIP) was used. MERRA data is a product of the National Aeronautics and Space Administration (NASA)’s Global Modeling and Assimilation Office (Rienecker et al., 2011). The data has undergone strict quality control through mechanisms also immensely improved through the observational assembly and advances made by the European Centers for Medium-Range Weather Forecast (ECMWF) Reanalysis-ERA (Rienecker et al., 2011). The use of MERRA data in climate research around the world have greatly increased due to its high data quality. Local success story in the use of MERRA data in climate research can be obtained in (Egeru et al., 2019).

Table 6.2: Summary of the elevation, longitude, latitude, data periods, and sources for Buginyanya, Kumi, and Nakapiripirit stations.

Climate data	Altitude (m.a.s.l.)	Longitude (degrees)	Latitude (degrees)	Data period	Data source
Buginyanya	1845	34.37	1.28	1980-2009	MERRA
Kumi	1153	34.15	1.51	1980-2009	MERRA
Nakapiripirit	861	34.77	1.71	1980-2009	MERRA

6.3.3 The Standardized Precipitation index (SPI)

The Standardized Precipitation Index (SPI) as given in Equation 6.1 was used to determine the sensitivity of the sub-catchment to extremely wet and dry periods (Table 6.3). SPI is calculated based on long-term precipitation data for a given location and a specific period. The scale of SPI can start from 1 month, 3 months, 6 months, 9 months, 12 months, 24 months, 36 months, and 48 months). The selection of the SPI scale is determined by the purpose for which it is being calculated. However, irrespective of the scale, SPI gives information on the impacts of wet/dry conditions on water availability for different needs. SPI measures the deviation in standard units between a dataset and its mean (Larbi et al., 2018); Funk et al., 2015). This study adopted the classification scheme of (Salehnia et al., 2017) in (Table 6.3). The (3-month, 6-month, and 12-month) SPIs were selected to identify the relative tendency towards above or below normal seasonal and annual precipitation (Oriangi, 2019). Each SPI scale is a comparison between the specific SPI time scale for the same period recorded in all the other years included in the dataset. As stated before, a 3-month SPI was selected to represent the seasonal estimations of precipitation and to provide a measure of the short-term moisture conditions. The 6-month and 12-month SPIs, on the other hand, were selected because they reflect the medium- and long-term moisture conditions, respectively. According to Nsubuga et al. (2019); WMO, (2012) and Hayes et al. (2000), information retrieved from the 6-month and 12-month SPIs can be used to capture variability in stream flow regimes and reservoir levels. The 6-month and 12-month SPIs can also provide information about the precipitation fallen during a 6-month and 12-month period (Hayes et al., 2000). According to Oriangi (2019), comparing short-term SPI with medium- and longer-

term scale SPIs is vital because a relatively normal or even a wet 3-month period can occur in the middle of a long-term drought, and that, in turn, can be captured only by a long-term SPI.

Table 6.3: SPI thresholds for wet and dry periods. Adopted from WMO, (2012)

Extremely we	2.00 and above
Very wet	1.5 to 1.99
Moderately wet	1.00 to 1.49
Normal	-0.99 to 0.99
Moderately dry	-1.00 to -1.49
Very dry	-1.50 to -1.99
Extremely dry	-2.00 and below

6.3.4 Mann–Kendall trend and Sen’s slope estimator

Trends and trend magnitudes were determined using the Mann–Kendall trend and Sen’s slope estimator (Salmi et al., 2002). The Mann–Kendall (MK) test is a nonparametric test does not require the data to be normally distributed, and is not very sensitive to missing data values (Salmi et al., 2002). The test has been used to detect both trends and shifts in climate and hydrological time-series datasets (Ndulue & Mbajiorgu, 2018; Jana et al., 2017). The test statistic, S , is based on the null hypothesis that there is no trend or serial correlation in a set of observations. S was calculated by using Equations 6.1 – 6.3:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (6.1)$$

where: x_j are the sequential data values, n is the length of the data set, and

$$\text{sgn}(t) = \begin{cases} 1, \text{for } t > 0 \\ 0, \text{for } t = 0 \\ -1 \text{ for } t < 0 \end{cases} \quad (6.2)$$

$$E(S) = 0 \quad (6.3)$$

In MAKESENS, the two-tailed test is used for four different significance levels of α : 0.1, 0.05, 0.01, and 0.001 (Salmi et al., 2002). At a certain probability level, H_0 is rejected in favor of H_1 if the absolute value of S equals or exceeds a specified value $S_{\alpha/2}$, where $S_{\alpha/2}$ is the smallest S which has the probability less than $\alpha/2$ to appear in case of no trend (Salmi et al., 2002). A positive/(negative) value of S indicates an upward/(downward) trend. The significance level of 0.001 means that there is a 0.1 % probability that the values x_i is from a random distribution and with that probability we make a mistake when rejecting H_0 of no trend. Thus, the significance level of 0.001 means that the existence of a monotonic trend is very probable. In the same way, the significance level of 0.1 means there is a 10 % probability that rejecting H_0 is a mistake. If n is at least 10, the normal approximation test is applied. The validity of the normal approximation reduces for the number of data values close to 10 for several tied values in the time series. The variance of S is first computed by following Equation 6.4 which takes into account that ties may be present:

$$Var(S) = \frac{1}{18} (n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)) \quad (6.4)$$

where: m is the number of tied groups and t_i is the size of the i^{th} tied group.

The standardized test statistics Z Equation 6.5 is computed as follows:

$$Z = \begin{cases} (S-1)/\sqrt{Var(S)} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ (S+1)/\sqrt{Var(S)} & \text{for } S < 0 \end{cases} \quad (6.5)$$

The presence of a statistically significant trend is confirmed using the Z value. A positive/(negative) value of Z indicates an upward/(downward) trend. The statistic Z has a normal distribution. This study used * to indicate trend at $\alpha = 0.05$ level of significance.

The Sen's is a nonparametric method used to estimate the true slope of an existing trend as change per year. The Sen's method can be used in cases where the trend can be assumed to be linear. This means that $f(t)$ in Equation 6.6 is equal to

$$f(t) = Qt + B \quad (6.6)$$

where Q is the slope and B is a constant.

The slope estimate Q in equation 6.7 is obtained by first calculating the slopes of all data value pairs

$$Q_i = \frac{x_j - x_k}{j - k} \quad (6.7)$$

Where $j > k$

If there are n values x_j in the time series, we get as many as $N = \frac{n(n-1)}{2}$ slope estimates Q_i . The

Sen's estimator of slope is the median of these N values of Q_i . The N values of Q_i are ranked from the smallest to the largest and the Sen's estimator Equation 6.8 is

$$Q = \begin{cases} Q_{[\frac{N+1}{2}]}, & \text{if } N \text{ is odd} \\ \frac{1}{2} \left(Q_{[\frac{N}{2}]} + Q_{[\frac{N+2}{2}]} \right), & \text{if } N \text{ is even} \end{cases} \quad (6.8)$$

A $100(1-\alpha)$ % two-sided confidence interval about the slope estimate is obtained by the nonparametric technique based on the normal distribution. The method is valid for n as small as 10 unless there are many ties.

The procedure in MAKESENS computes the confidence interval at two different confidence levels; $\alpha = 0.01$ and $\alpha = 0.05$, resulting in two different confidence intervals Equation 6.9.

At first, we compute

$$C_\alpha = Z_{1-\frac{\alpha}{2}} \sqrt{VAR(S)} \quad (6.9)$$

where $VAR(S)$ has been defined in equation (5.4), and $Z_{1-\alpha/2}$ is obtained from the standard normal distribution. Next $M_1 = \frac{N-C_\alpha}{2}$ and $M_2 = \frac{N+C_\alpha}{2}$ are computed. The lower and upper limits of the confidence interval, Q_{min} and Q_{max} , are the $(M_1)^{th}$ largest and the $(M_2 + 1)^{th}$ largest of the N ordered slope estimates Q_i . If M_1 is not a whole number, the lower limit is interpolated. Correspondingly, if M_2 is not a whole number the upper limit is interpolated.

To obtain an estimate of B in equation 15, the n values of differences $x_i - Q_{it}$ are calculated. The median of these values gives an estimate of B (Sirois 1998). The estimates for the constant B of line of 95 % confidence interval are calculated by a similar procedure.

6.3.5 Climate change scenarios

The near future 2025-2040 climate data was statistically downscaled from the 29 GCMs (Appendix 3) of the IPCC Fifth Coupled Model Inter comparison Project (CMIP5) using delta method of the Agricultural Model Inter-comparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013). Five climate models representing each of regimes Cool-wet, Cool-dry, Hot-wet, Hot-dry, and Middle under two Representative Concentration Pathways (RCP) 4.5 and RCP8.5, respectively were selected using the representative temperature and precipitation sub-setting approach (Ruane & McDermid, 2017).

There are four climate scenarios called the Representative Concentration Pathways (RCPs) namely RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 developed by IPCC fifth assessment report (IPCC, 2014). RCP 2.6 is a pathway where radiative forcing peaks at approximately 3 Wm^{-2} before 2100 and then declines assuming constant emissions after 2100; RCP4.5 and RCP 6.0 are two intermediate stabilization pathways in which radiative forcing is stabilized at approximately 4.5 Wm^{-2} and 6.0 Wm^{-2} after 2100 assuming constant concentrations after 2150; RCP 8.5 is a high pathway for which radiative forcing reaches greater than 8.5 Wm^{-2} by 2100 and continues to rise for some amount of time assuming constant emissions after 2100 and constant concentrations after 2250 (Moss et al., 2008).

This study used the representative temperature and precipitation change sub-setting approach. According to Ruane & McDermid (2017), the representative temperature and precipitation change sub-setting approach provides practical and coherent basis for the quantitative determination of useful GCMs subsets while conserving resources and enabling physical and statistical analysis of GCM projections. These subsets were obtained by dividing the GCMs outputs (climate regimes) in to quadrants consisting of Cool-wet, Cool-dry, Hot-wet and Hot-dry in addition to a fifth one called Middle based on how far the GCM's precipitation and temperature change is in relation to the ensemble median. A climate regime is classified as relatively wet or cool, hot or dry, and middle. A climate regime is relatively wet or cool when its

precipitation and temperature changes are below the ensemble median. Hot or dry when its temperature and precipitation change are above the ensemble median for all the GCMs, and middle when its precipitation and temperature change are near the point of intersections of the four quadrants/the ensemble median for all the GCMs. The final selection of a GCM within a quadrant (climate regime) was done by first obtaining the average precipitation and temperature change for all the GCMs within the selected climate regime and marking it by a dot. The GCM whose precipitation and temperature change were closest to the dot was then selected for the study. The procedure was repeated for all the five climate regimes for each climate scenario. In cases where two or more GCMs appeared to be equidistant from the dot, one was randomly selected. Outputs of the five GCMs for each of the three virtual weather stations were used in the comparisons of 1980-2009 and 2025-2040 climate of Sironko catchment under the two emission scenarios RCP 4.5 and RCP 8.5 respectively (Appendices 4, 5, 6, and 7). The RCP 4.5 and RCP 8.5 were chosen because they are the most commonly used in assessing future climate/impacts (Egeru et al., 2019; Molina-Navarro et al., 2018; Shrestha et al., 2018).

6.3.6 Data analysis

Data analysis was carried out at the individual stations' level based on four seasons December, January, February (DJF); March, April, May (MAM), June, July, August (JJA), and September, October, November (SON). Descriptive statistics (mean, standard deviation, coefficient of variation) were performed in Microsoft excel 2016. Trends and trend magnitudes were determined using the Mann–Kendall trend and Sen's slope estimator in the MAKESNS program developed by the Finished Meteorological Institute as detailed above. On the other hand, p-values of trends were generated by linear regression in IBM SPSS 20 package.

6.4 Results

6.4.1 Seasonal variability in rainfall and temperature in Sipi sub-catchment

The results of seasonal variability in Sipi sub-catchment are presented in (Table 6.4). The result has been presented for the four seasons DJF, MAM, JJA, and SON, respectively. However, the discussion has been biased to the two rainfall seasons MAM and SON due to their implications on subsistence agriculture and livelihoods. The mean of MAM rainfall was higher in Kapchorwa station 189.58 mm than in in Buginyanya station 188.87 mm. In SON, however, Kapchorwa

station recorded the lowest mean rainfall of 173.73 mm while it was highest in Buginyanya station 189.00 mm. The CV for seasonal rainfall indicates that SON rainfall is highly variable ($CV > 30$) compared to MAM season rainfall which is less variable ($CV < 20$) or moderately variable ($20 < CV < 30$). The long-term mean temperature recorded in MAM was 21.83 °C for Kapchorwa station, 22.29 °C for Buginyanya, and 22.06 °C for the whole Sipi sub-catchment. Kapchorwa station recorded the lowest mean temperature in SON 21.28 °C as compared with 21.67 °C in Buginyanya station. Over the sub-catchment, the mean temperature in SON was 21.48 °C.

Table 6.4 Seasonal variabilities in rainfall, minimum, maximum and mean temperature 1981-2015

Buginyanya								
	DJF		MAM		JJA		SON	
Statistics	Rainfall (mm)	T- mean (°C)	Rainfall (mm)	T- mean (°C)	Rainfall (mm)	T- mean (°C)	Rainfall (mm)	T- mean (°C)
Mean	49.27	22.77	188.87	22.29	190.04	20.89	189.00	21.67
Standard deviation	26.86	0.57	46.84	0.58	76.14	1.04	64.10	0.64
CV	54.52	2.51	24.80	2.60	40.07	4.96	33.92	2.97
Kapchorwa								
Mean	50.89	22.37	190.28	21.83	176.11	20.35	173.73	21.28
Standard deviation	30.98	0.63	49.74	0.70	66.88	1.07	60.76	0.72
CV	60.88	2.81	26.14	3.21	37.97	5.28	34.97	3.38
Sipi sub-catchment								
Mean	50.08	22.57	189.58	22.06	183.08	20.62	181.37	21.48
Standard deviation	28.78	0.58	47.61	0.62	71.14	1.05	60.09	0.67
CV	57.46	2.59	25.11	2.81	38.86	5.08	33.13	3.12

6.4.2 Annual variability in rainfall, temperature and river flow in Sipi sub-catchment

The results in Table 6.5 indicate that annual rainfall has been very stable in Buginyanya, Kapchorwa, and over the sub-catchment. The annual rainfall and mean temperature also reflected variability. The long-term mean temperature was similarly higher in Buginyanya by 0.5 °C and

in Kapchorwa by 0.02 °C against that over the entire sub-catchment. Annual mean flow of River Sipi showed a very high level of variability CV = 45.7 %.

Table 6.5: Annual variability of rainfall, mean temperature 1981-2015, and flow 1998-2015

Variables	Buginyanya			Kapchorwa			Sub-catchment		
	Mean	Standard deviation	CV	Mean	Standard deviation	CV	Mean	Standard deviation	CV
Rainfall (mm)	1851.6	466.1	25.2	1773.4	444.5	25.1	1812.3	451.6	24.9
T mean (°C)	21.9	0.6	2.8	21.5	0.8	3.2	21.7	0.6	2.9
Flow (m ³ /s)							2.34	1.1	45.7

6.4.3 Annual patterns of rainfall and river flow in Sipi sub-catchment

According to Figure 6.2, annual rainfall in both Buginyanya and Kapchorwa ranged from about 1500 to 2000mm between 1998 and 2012 except in 2007 where Buginyanya received up to 3783.30 mm and Kapchorwa received 3403.2 mm of annual rainfall respectively. Figure 6.2 also indicates a shift in annual rainfall amount above 2000 mm in both Buginyanya and Kapchorwa, starting from 2013. On the other hand, annual mean flow remained below 1.95 m³/s from 1998 to 2005, where it hiked to 3.43 m³/s in 2007 before dropping to 1.6 m³/s in 2009. Where it steadily roused to 3.03 m³/s in 2014 before declining to 1.87 m³/s in 2015.

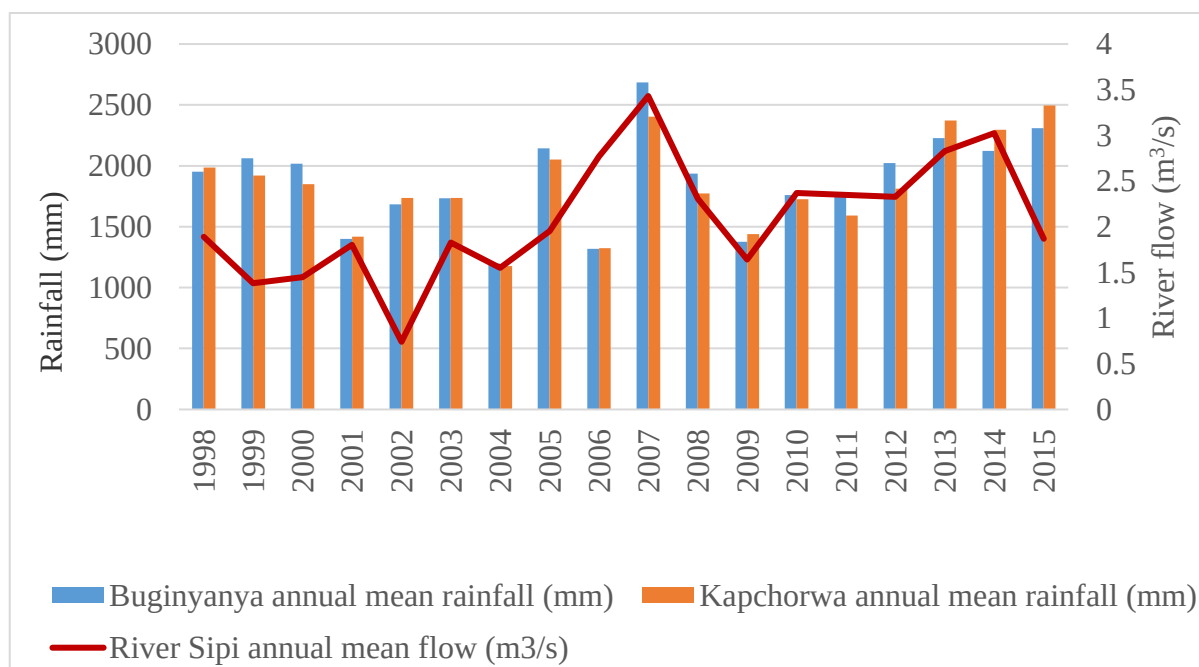


Figure 6.2: Annual patterns of rainfall in Buginyanya and Kapchorwa and river flow 1998-2015

6.4.4 Frequency of extremely wet and dry events in Sipi sub-catchment

The occurrence of extremely wet and dry events in the Sipi sub-catchment Table 6.6 and Figure 6.3 based on the 3-month SPI revealed that there were six extremely wet years in the Sipi sub-catchment between 1990 and 2015. The first extremely wet period occurred from February to June 1990, the second occurred from January to June 1998, the third occurred from March to May 2002, the fourth from May to September 2005, the fifth from July 2007 and lasted till April 2008 while the sixth was from April to September 2015. On the other hand, there were five extreme dry periods under the 3-month SPI in the Sipi sub-catchment for the period 1981–2015. The first dry period was between January 1994 and April 1994. In 2004, it was from July to October. In 2006, it began in June and lasted till August. In 2009, it was from August to October, and in 2012, it was from March to June. Most of the extreme events were in the second rainfall season. This high variability in the second rainfall season SON has also been confirmed under section 6.4.1 and later for the projection between 2025-2040 under section 6.5.5.

Table 6.6 Frequency of extremely wet and dry events in Sipi sub-catchment between 1981 and 2015 under the 3-month, 6-month, and 12-months SPI

	Frequency		Frequency	
% SPI	Extremely wet	Extremely dry	Extreme events pre-2000	Extreme events post 2000s
3-month	4	5	3	6
6-month	3	2	2	4
12-month	2	2	0	4

There were more extreme events (14) during the post-2000 period as compared with five in the pre-2000 Table 6.6 that. It, therefore, implies that the Sipi sub-catchment has become more prone to extreme events in the recent period than before.

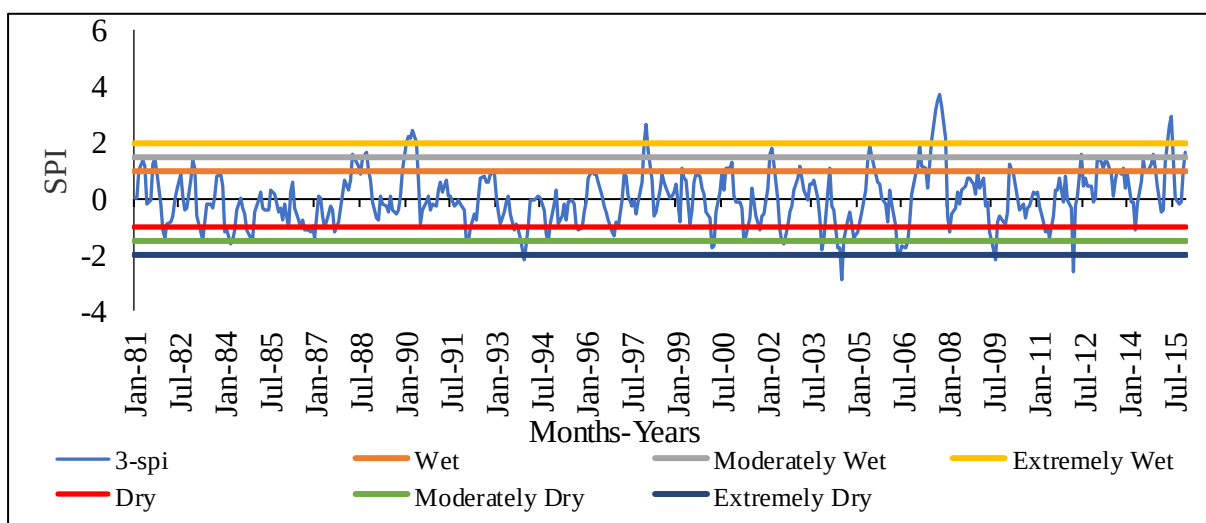


Figure 6.3: Three months SPI over Sipi sub-catchment (1981-2015)

The 6-month SPI Figure 6.4 revealed that there were four extremely wet periods during the period 1981–2015. The first extremely wet months occurred from March to July 1990. The second extremely wet months were from April to May 1998. The third extremely wet months lasted from July 2007 to May 2008. The fourth was from June 2015 to September 2015. On the other hand, there were two extremely dry periods recorded under the 6-month SPI. The first one occurred between July and October 2004 while the second occurred between July and October

2006. All the extremely dry periods under 6-month SPI were in the second rainfall season. On the other hand, two out of three of the extreme wet months under the 6-month SPI were also in the second rainfall season. Therefore, the extreme events under the 6-month SPI were more pronounced in the second rainfall season.

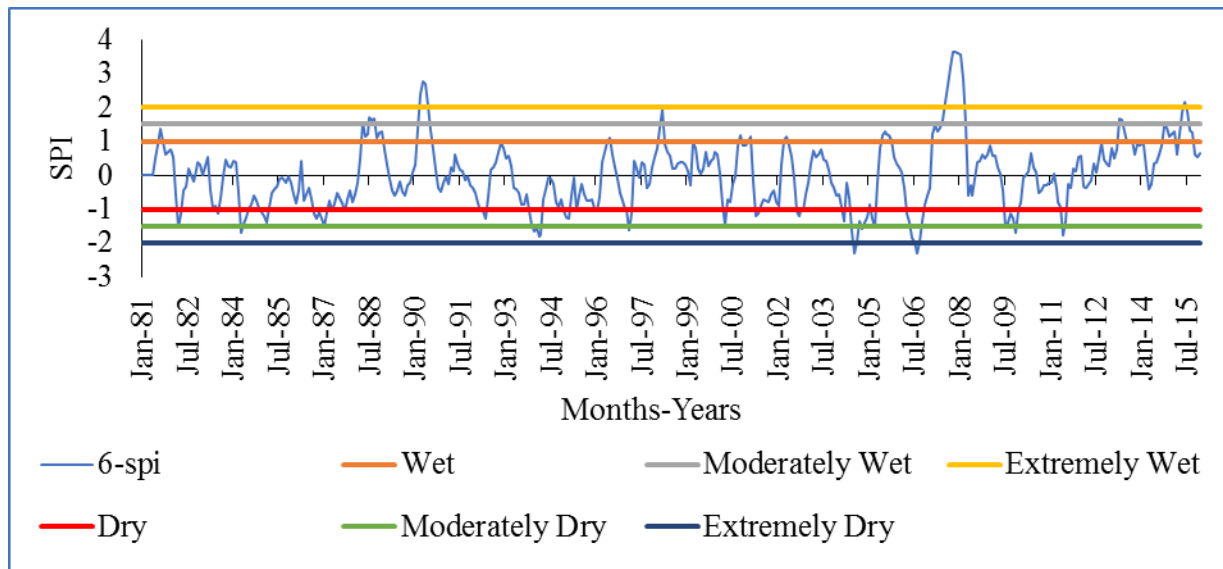


Figure 6.4: Six months SPI over Sipi sub-catchment 1981-2015

The 12-month SPI revealed that there were two extremely wet periods and two extremely dry periods over the sub-catchment (Figure 6.5). The first extremely wet event occurred between September 2007 and October 2008. The second one occurred between June and August 2015. For the extremely dry periods, the first occurred between August and September 2004, while the second period started in February 2005 and lasted until April. The 12-month SPI revealed that the two extremely wet events and one extremely dry event all occurred in the second rainfall season.

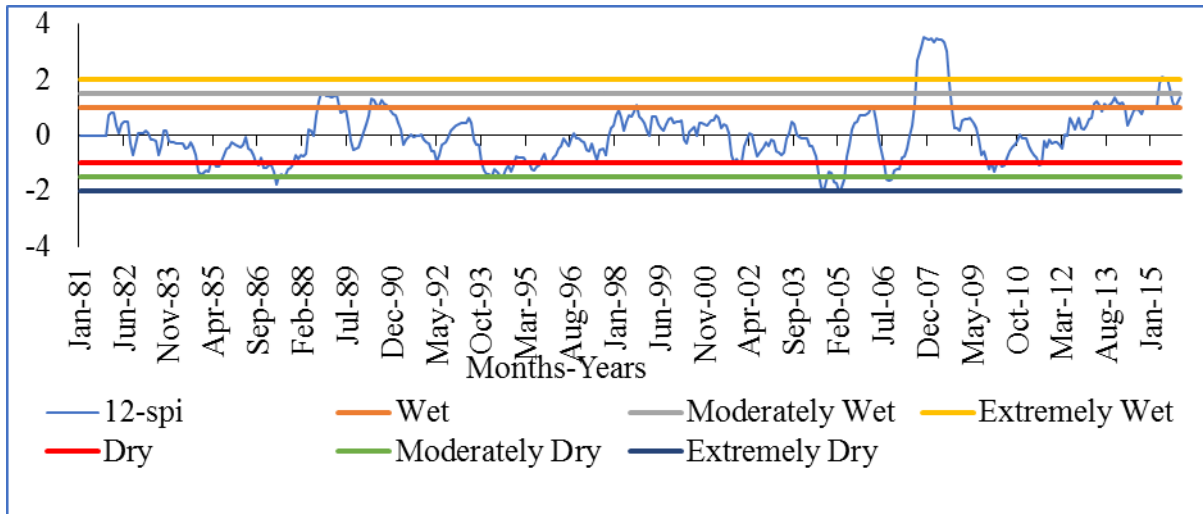


Figure 6.5: Twelve months SPI over Sipi sub-catchment 1981-2015

6.4.4 Seasonal and annual trends of rainfall, temperature and river flow in Sipi sub-catchment 1998-2015

Trend analysis revealed increasing seasonal and annual rainfall and mean temperature (Table 6.7). The trends were not significant for seasonal and annual rainfall. The largest increase in MAM rainfall occurred in Kapchorwa station 2.1 mm as revealed by the Sens' slope. In SON, the increase in rainfall ranged from 3.56 mm in Buginyanya to 3.9 mm in Kapchorwa and to 4.11 mm at a sub-catchment level. Generally, mean temperature showed significant increasing trends across the sub-catchment between 1981 and 2015 Figures 6.6 and 6.7 except for MAM season in Buginyanya. Sens slope estimates indicate that mean temperature for MAM increased by 0.01 °C, while, in SON, it increased by 0.03 °C per season across Sipi sub-catchment between 1981-2015.

Table 6.7 Seasonal and annual trends of rainfall mean temperature 1981–2015 for Buginyanya, Kapchorwa, whole sub-catchment, and river flow for Annual, MAM, and SON seasons 1998–2015

Buginyanya				Buginyanya		
Time series	(Rainfall)			(Mean temperature)		
Time series	Test Z	Q	p-value	Test Z	Q	p-value
DJF	1.62	1.81	0.12	2.39*	0.02	0.00
MAM	0.36	0.80	0.07	1.33	0.01	0.18
JJA	0.45	1.64	0.71	2.95*	0.05	0.01
SON	1.51	3.36	0.15	2.13*	0.03	0.01
Annual	1.05	8.68	0.25	3.01*	0.02	0.01
Kapchorwa				Kapchorwa		
DJF	2.58*	3.15	0.03	3.15*	0.02	0.00
MAM	0.77	2.11	0.34	1.93*	0.01	0.03
JJA	0.94	3.77	0.47	2.87*	0.05	0.00
SON	1.68	3.85	0.06	1.48*	0.03	0.02
Annual	1.65	9.46	0.06	2.84*	0.03	0.00
Sipi sub-catchment				Sipi sub-catchment		
DJF	2.27	2.43	0.06	3.32*	0.02	0.00
MAM	0.71	1.71	0.50	1.45*	0.01	0.06
JJA	0.94	2.47	0.59	2.90*	0.05	0.01
SON	1.59	4.11	0.09	1.85*	0.03	0.01
Annual	1.52	9.16	0.13	2.90*	0.03	0.00
Sipi sub-catchment flow						
	Z	Q		p-vale		
MAM Flow (m3/s)	2.50*	0.08		0.04		
SON Flow (m3/s)	1.52	0.17		0.06		
Annual Flow (m3/s)	2.50*	0.10		0.02		

Marked * denotes trend at $\alpha = 0.05$ level of significance.

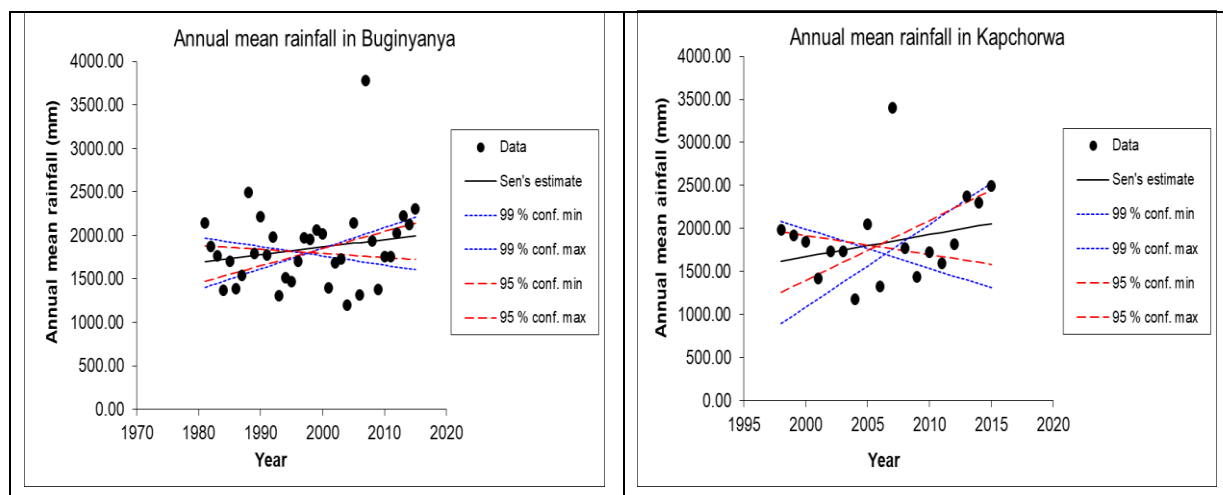


Figure 6.6 Time series of annual rainfall in Buginyanya and Kapchorwa (1981–2015)

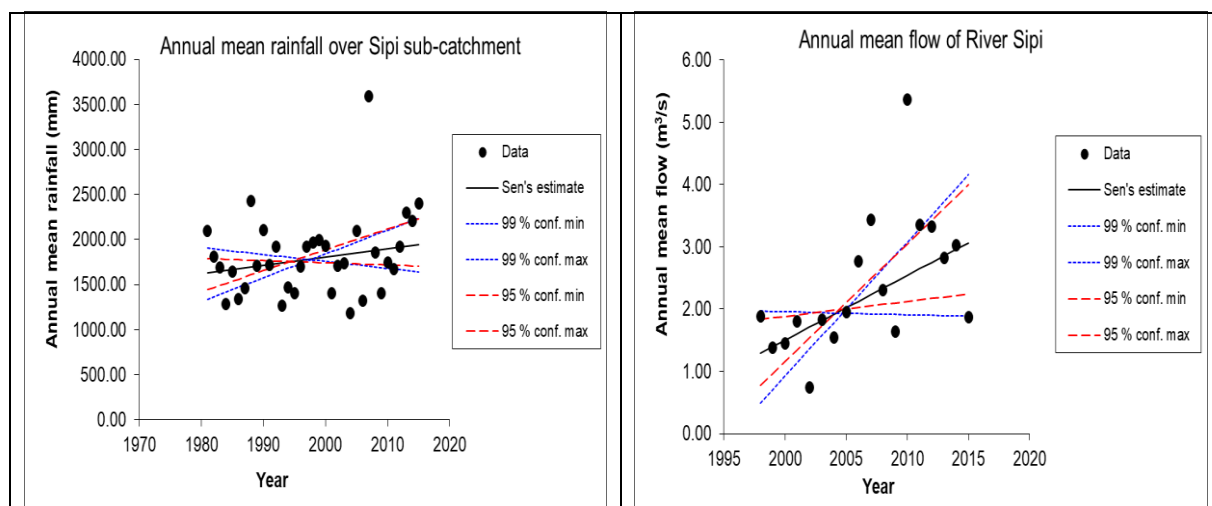


Figure 6.7 Time series of annual rainfall over Sipi sub-catchment (1981–2015) and River Sipi flow 1998–2015.

6.5.1 Seasonal and annual rainfall variability in Sironko catchment between 1980-2009

Baseline variability of seasonal and annual rainfall total in Sironko catchment between 1980 and 2009 is presented in (Table 6.8). The result shows that DJF and SON seasons are highly variable. The coefficient of variation (CV) for DJF ranged from 69.71 % in Buginyanya, 53.15 % in Nakapiripirit, and 40.68 % in Kumi stations while the CV for SON are in the ranged of 26.04 % in Kumi station to 30.75 % in Nakapiripirit, and to 37.41 % in Buginyanya station respectively. The first rainfall season MAM and annual rainfall are moderately variable with CVs for MAM

and annual rainfall ranging from 21.20 % and 17.69 % in Buginyanya to 19.4 % and 14.31 % in Kumi, and to 17.14 % and 13.72 % in Nakapiripirit stations respectively.

Table 6.8 Baseline seasonal and annual rainfall total variability in Sironko catchment from 1980-2009

Buginyanya					
Statistics	DJF	MAM	JJA	SON	Annual
Mean	62.404	344.10	311.10	207.50	925.10
Standard deviation	43.50	73.91	65.96	77.62	163.66
Coefficient of variation (%)	69.71	21.48	21.20	37.41	17.69
Kumi					
Mean	106.93	431.11	331.9	322.66	1192.6
Standard deviation	43.5	73.91	65.96	77.62	163.66
Coefficient of variation (%)	40.68	17.14	19.87	24.06	13.72
Nakapiripirit					
Mean	79.61	368.67	387.76	290.38	1126.43
Standard deviation	42.31	71.7	70.43	89.29	161.19
Coefficient of variation (%)	53.15	19.45	18.16	30.75	14.31

6.5.2 Seasonal and annual mean temperature variability in Sironko catchment between 1980-2009

The baseline variability in seasonal and annual mean temperature in Sironko catchment between 1980-2009 is presented in (Table 6.9). The result shows that JJA has been the coolest season in the catchment with mean temperature ranging from 21.91 °C in Buginyanya to 21.74 °C in Nakapiripirit, and to 23.48 °C in Kumi stations respectively. The warmest season in the catchment has been DJF with highest mean temperature for the baseline period of 26.22 °C recorded in Kumi, followed by 24.01 °C in Nakapiripirit, and lastly 24.18 °C in Buginyanya stations respectively. Similar to rainfall pattern, mean temperature variation is highest in Buginyanya where seasonal mean temperature CV ranged from 3.08 % in JJA to 4.06 % in MAM for Buginyanya station; 2.14 % in JJA to 2.87 % in MAM for Kumi station; and from 2.71 % in DJF and SON to 3.06 % in MAM in Nakapiripirit stations respectively. The station with the least mean temperature variation is Kumi where CV ranged from 2.87 % in MAM to 1.83 % for annual.

Table 6.9: Descriptive statistics of seasonal and annual mean temperature in Buginyanya station 1980-2009

Buginyanya					
Statistics	DJF	MAM	JJA	SON	Annual
Mean	24.18	23.79	21.91	22.63	23.12
Standard deviation	0.89	0.97	0.68	0.81	0.74
Coefficient of variation	3.68	4.06	3.08	3.57	3.2
Kumi					
Mean	26.22	25.63	23.48	24.64	24.98
Standard deviation	0.67	0.73	0.5	0.65	0.46
Coefficient of variation	2.54	2.87	2.14	2.62	1.83
Nakapiripirit					
Mean	24.01	23.5	21.74	22.83	23.01
Standard deviation	0.7	0.72	0.63	0.62	0.57
Coefficient of variation	2.93	3.06	2.88	2.71	2.48

6.5.3 Mann-Kendall trends and Sen's slope estimates of seasonal and annual rainfall total in Sironko catchment between 1980-2009

The Mann-Kendall trends and Sen's slope estimates of seasonal and annual rainfall total in Sironko catchment 1980-2009 baseline is presented in (Table 6.10). The result shows that seasonal and annual rainfall trends increased across the Sironko catchment between 1980 and 2009 except for (MAM) rainfall in Kumi and Nakapiripirit stations and annual rainfall in Buginyanya station respectively. The trends (increasing and decreasing) were however, not significant except for SON in Kumi station ($p = 0.01$) and $R^2 = 0.20$ Figure 6.8 and Nakapiripirit station ($p = 0.02$) $R^2 = 0.16$ Figure 6.9 respectively.

Table 6.10: Mann-Kendall trends and Sen's slope estimates of seasonal and annual rainfall total in Sironko catchment from 1980 to 2009 baseline.

Stations	Buginyanya			Kumi			Nakapiripirit		
Time series	Test Z	Q (mm)	p-value	Test Z	Q (mm)	p-value	Test Z	Q (mm)	p-value
DJF	1.75	2.66	0.05	2.78	1.91	0.08	1.68	1.74	0.05
MAM	0.21	0.80	0.89	-0.80	-1.38	0.39	-1.11	-2.04	0.23
JJA	0.14	0.56	0.70	1.14	1.70	0.50	1.43	2.62	0.24
SON	0.71	2.36	0.21	2.21*	3.78	0.04	2.00*	4.66	0.04
Annual	-0.18	-1.09	0.91	1.36	4.36	0.14	1.36	5.56	0.07

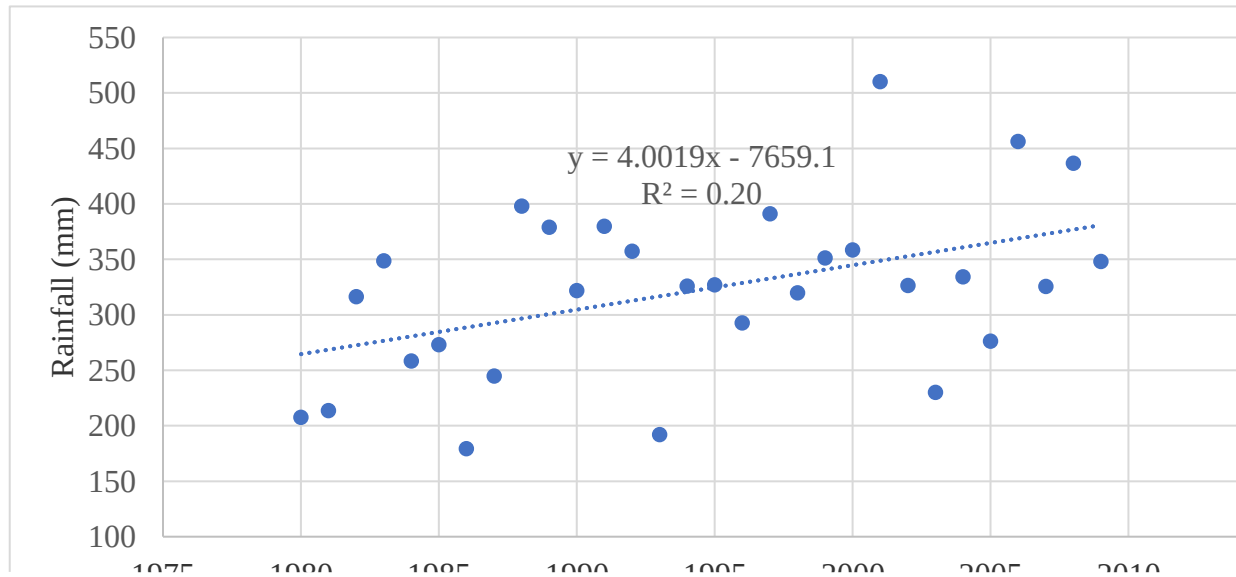


Figure 6.8: Scatter plots for SON seasonal rainfall in Kumi stations for baseline period 1980-2009

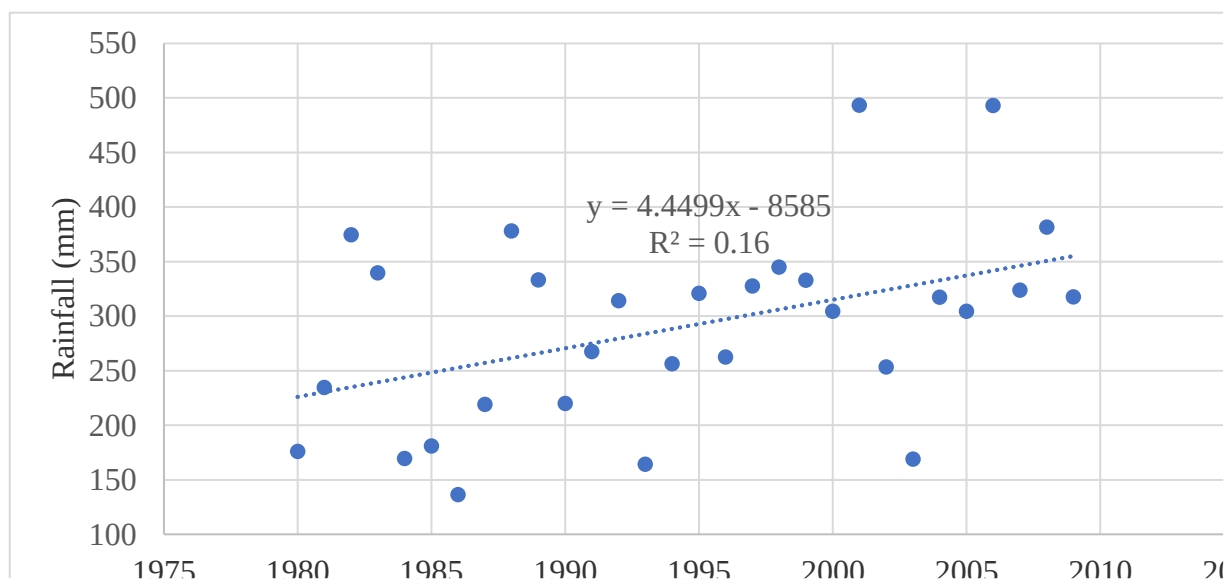


Figure 6.9: Scatter plots for SON seasonal rainfall in Nakapiripirit station for baseline period from 1980 to 2009

6.5.4 Mann-Kendall trends and Sen's slope estimates of seasonal and annual mean temperature in Sironko catchment 1980-2009

Baseline Mann-Kendall trends and Sen's slope estimates of seasonal and annual mean temperature in Sironko catchment for the period 1980-2009 is presented in (Table 6.11). The Table shows that mean temperature significantly increased over DJF in Kumi and Nakapiripirit stations ($p = 0.02$) Table 6.11 and $R^2 = 0.35$ Figure 6.10 and ($p = 0.00$) Table 6.11 and $R^2 = 0.48$ Figure 6.11, and on annual time frame in Kumi station ($p = 0.03$) Table 6.11 and $R^2 = 0.38$ Figure 6.12 respectively. Generally, baseline seasonal and annual temperature pattern suggests increasing mean temperature across Sironko catchment from 1980 to 2009.

Table 6.11 Mann-Kendall trends and Sen's slope estimates of seasonal and annual mean temperature in Buginyanya, Kumi, and Nakapiripirit stations from 1980 to 2009

Stations	Buginyanya			Kumi			Nakapiripirit		
Time series	Test Z	Q (°C)	p-value	Test Z	Q (°C)	p-value	Test Z	Q (°C)	p-value
DJF	3.07	0.04	0.42	3.25*	0.05	0.00	4.03*	0.06	0.00
MAM	3.21	0.05	0.51	2.71	0.05	0.19	3.71	0.05	0.07
JJA	1.39	0.01	0.78	1.89	0.02	0.08	2.00	0.02	0.98
SON	1.82	0.02	0.99	1.11	0.02	0.36	2.71	0.03	0.63
Annual	3.53	0.03	0.71	3.64*	0.03	0.02	3.82	0.03	0.10

Q = Sens' slope marked * if trend at $\alpha = 0.05$ level of significance

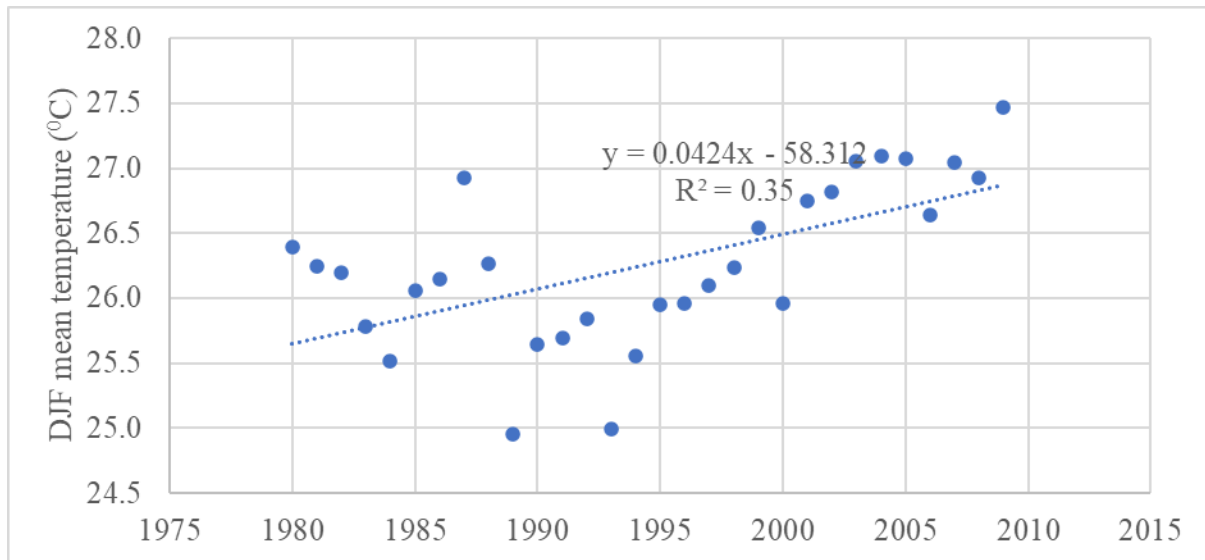


Figure 6.10: Scatter plots for DJF mean temperature in Kumi station for baseline period from 1980 to 2009

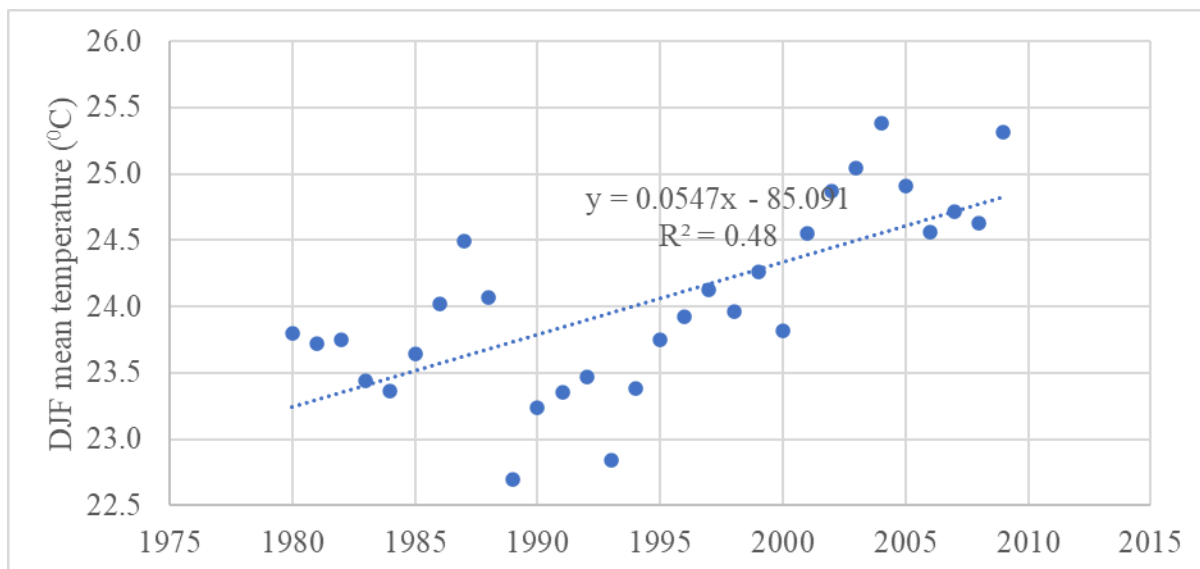


Figure 6.11: Scatter plots for DJF mean temperature in Nakapiripirit station for baseline period from 1980 to 2009

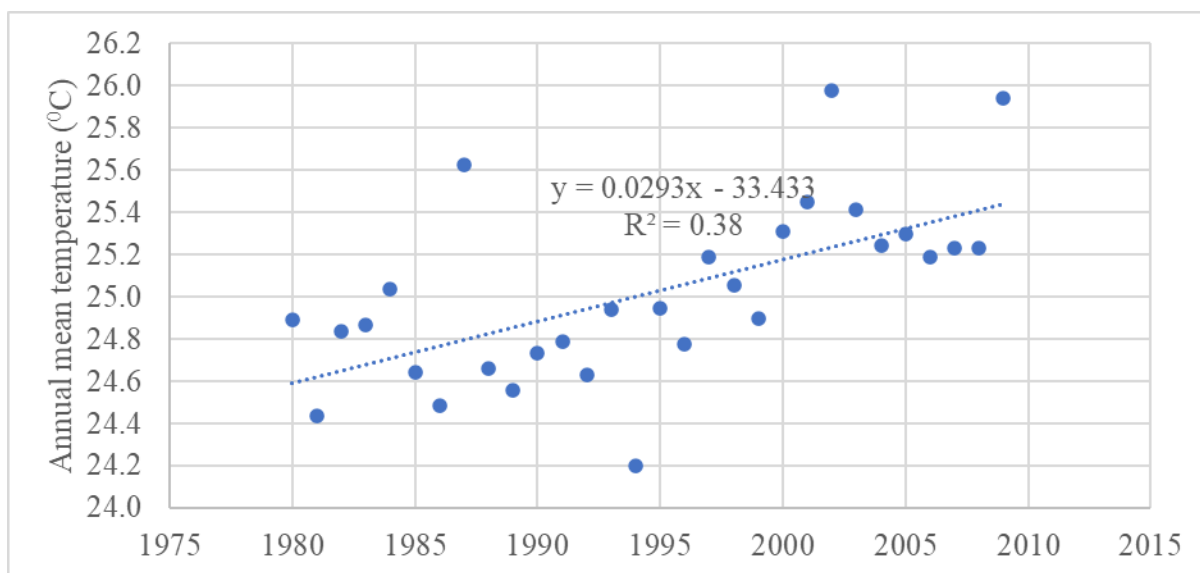


Figure 6.12: Scatter plots for annual mean temperature in Kumi station for baseline period from 1980 to 2009

6.5.5 Projected changes in seasonal and annual rainfall total in Sironko catchment between 2025 and 2040 under Hot-dry and Cool-wet climate regimes

The projected changes in seasonal and annual rainfall total in Sironko catchment for the period 2025-2050 relative to baseline 1980-2009 is presented in Table 6.12 and 6.13 for Hot-dry and

Cool-wet climate regimes under RCP 4.5 and RCP 8.5 respectively. The results in Table 6.12 indicate that in the period 2025-2040 seasonal and annual rainfall total in Buginyanya will increase in the Hot-dry regime for both RCP 4.5 and RCP 8.5 respectively. The first rainfall season MAM will have higher mean than the second rainfall season SON and only DJF rainfall will vary highly CV = 30.18 % under RCP 8.5 (Hare, 2003). The highest change in seasonal rainfall under RCP 4.5 will be recorded in SON (164.90 mm) while the lowest will be in DJF (61.63 mm). Similarly, under RCP 8.5 the highest change in seasonal rainfall total will be recorded in SON (237.22 mm) and the lowest in DJF (76.83 mm) respectively.

Table 6.12: Projected change in seasonal and annual rainfall total under Hot-dry regime for RCP 4.5 and RCP 8.5 in Buginyanya station from 2025 to 2040

Scenario s	Hot-dry RCP 4.5					Hot-dry RCP 8.5				
Statistics	DJF	MA M	JJA	SON	Annua l	DJF	MA M	JJA	SON	Annua l
Mean	124.03	424.15	374.44	372.40	1295.01	227.73	547.38	305.16	391.79	1472.06
Standard deviation	34.85	55.29	82.68	77.15	136.53	68.74	72.85	66.87	84.29	158.45
Coefficient of variation	28.10	13.03	22.08	20.72	10.54	30.18	13.31	21.91	21.51	10.76
Change in mean	61.63	80.05	63.34	164.90	369.91	76.83	122.04	147.06	237.22	583.15

From 2025 to 2040 seasonal and annual rainfall total in Buginyanya for Cool-wet regimes will increase under both RCP 4.5 and RCP 8.5, respectively (Table 6.13). Again, the first rainfall season MAM will have higher mean than the second rainfall season SON except under RCP 8.5. The highest change in seasonal rainfall under RCP 4.5 will be recorded in SON (237.22 mm) while the lowest will be in DJF (76.83mm). Similarly, under RCP 8.5 the highest change in seasonal rainfall total will be recorded in SON (214.97 mm) but unlike under the Hot-dry regime, for the Cool-wet regime the lowest seasonal rainfall change in mean will be recorded in MAM (17.02 mm).

Table 6.13 Projected change in seasonal and annual rainfall total under Cool-wet regime for RCP 4.5 and RCP 8.5 in Buginyanya station from 2025 to 2040

Scenario	Cool-wet RCP 4.5					Cool-wet RCP 8.5				
s										
Statistics	DJF	MA M	JJA	SON	Annua l	DJF	MA M	JJA	SON	Annua l
Mean	139.2 3	466.1 4	458.1 6	444.7 2	1508.2 5	119.1 3	361.1 3	387.3 8	422.4 7	1290.1 1
Standard deviation	37.59	61.41	101.7 6	90.13	166.48	34.27	52.24	86.23	84.37	146.89
Coefficient of variation	27.00	13.17	22.21	20.27	11.04	28.76	14.46	22.26	19.97	11.39
Change in mean	76.83	122.0 4	147.0 6	237.2 2	583.15	56.73	17.02	76.28	214.9 7	365.01

In Kum station on the other hand, MAM rainfall under RCP 4.5 and JJA rainfall under RCP 8.5 for Hot-dry climate regime between 2025 and 2040 will decrease by 42.86 mm and 26.74 mm respectively relative to the corresponding seasons mean from 1980 to 2009 (Table 6.14). It is also seen from Table 6.14 that only DJF total rainfall under RCP 8.5 can be categorized as highly variable $CV = 30.18\%$ (Hare, 2003). The first rainfall season MAM will have a higher mean than the second rainfall season SON under RCP 4.5 whereas, the reverse is true under RCP 8.5. Although MAM rainfall will have a higher mean than SON rainfall under RCP 4.5, the mean will be less than that for MAM rainfall during baseline period possibly due to extreme rainfall between 2025 and 2040.

Table 6.14: Projected change in seasonal and annual rainfall total under Hot-dry regime for RCP 4.5 and RCP 8.5 in Kumi station from 2025 to 2040

Scenario	Hot-dry RCP 4.5					Hot-dry RCP 8.5				
s										
Statistics	DJF	MA M	JJA	SON	Annua l	DJF	MA M	JJA	SON	Annua l
Mean	121.3 8	388.2 5	375.3 3	437.5 6	1322.5 2	227.7 3	547.3 8	305.1 6	391.7 9	1472.0 6
Standard deviation	34.09	52.15	84.18	87.52	144.51	68.74	72.85	66.87	84.29	158.45
Coefficient of variation	28.08	13.43	22.43	20.00	10.93	30.18	13.31	21.91	21.51	10.76
Change in mean	14.45	- 42.86	43.43	114.9 0	129.92	120.8 0	116.2 7	- 26.74	69.13	279.46

For Cool-wet climate regime in Kumi station meanwhile, only JJA rainfall will record a mean which is 87.75 mm less than baseline JJA rainfall (Table 6.15). However, none of the seasons show high variability in rainfall under both RCP 4.5 and RCP 8.5 CV less than 30 % (Hare, 2003). Again, the first rainfall season MAM will have higher means under both RCP 4.5 (466.14 mm) and RCP 8.5 (459.11mm) than the second rainfall season SON (444.72mm) under RCP 4.5 and SON (346.49 mm) under RCP 8.5 respectively.

Table 6.15: Projected change in seasonal and annual rainfall total in Sironko catchment under Cool-wet regime for RCP 4.5 in Kumi station from 2025 to 2040

Scenario	Cool-wet RCP 4.5					Cool-wet RCP 8.5				
s										
Statistics	DJF	MA M	JJA	SON	Annua l	DJF	MA M	JJA	SON	Annua l
Mean	139.2 3	466.1 4	458.1 6	444.7 2	1508.2 5	215.8 9	459.1 1	244.5 5	346.4 9	1266.0 4
Standard deviation	37.59	61.41	101.7 6	90.13	166.48	59.42	68.59	54.12	78.87	141.79
Coefficient of variation	27.00	13.17	22.21	20.27	11.04	27.52	14.94	22.13	22.76	11.20
Change in mean	32.30	35.03	126.2 6	122.0 6	315.65	108.9 6	28.00	- 87.35	23.83	73.44

The projected changes in seasonal and annual rainfall total in Nakapiripirit station between 2025 and 2040 relative to baseline period 1980-2009 will be higher except for MAM total rainfall whose mean will be 28.88 mm less than for the baseline under Hot-dry and for both RCP4.5 and RCP 8.5 respectively (Table 6.16). According to Hare (2003), only DJF rainfall will be categorized as highly variable CV = 49.40 % and 47.04% under RCP 4.5 and RCP 8.5 respectively. Furthermore, the first rainfall season MAM will have a mean of 339.79 mm which is less than the second rainfall Season SON whose mean will be 409.98 mm under RCP 4.5. However, the reverse is true under RCP 8.5 where the mean of MAM rainfall will be 473.21 mm while that of SON will be 373.24 mm respectively.

Table 6.16: Projected change in seasonal and annual rainfall total under Hot-dry regime for RCP 4.5 and RCP 8.5 in Nakapiripirit station from 2025 to 2040

Scenarios	Hot-dry RCP 4.5					Hot-dry RCP 8.5				
Statistics	DJF	MA M	JJA	SON	Annua l	DJF	MA M	JJA	SON	Annua l
Mean	95.5 3	339.7 9	451.2 9	409.9 8	1296.5 9	147.2 4	473.2 1	459.9 8	373.2 4	1453.6 7
Standard deviation	47.1 9	67.53	76.52	99.46	151.56	69.27	95.57	80.07	89.45	171.38
Coefficient of variation	49.40	19.87	16.96	24.26	11.69	47.04	20.20	17.41	23.96	11.79
Change in mean	15.9 2	- 28.88	63.53	119.6 0	170.16	67.63	104.5 4	72.22	82.86	327.24

Looking at Cool-wet climate regime in Nakapiripirit, the result in Table 6.17 shows that only JJA and SON rainfall total will have means that are less than the corresponding JJA and SON rainfall total during baseline period by 53.22 mm and 53.46 mm under RCP 4.5 and RCP 8.5 respectively. Furthermore, only DJF rainfall can be categorized as highly variable CV of 48.27 % and 50.38 % for RCP 4.5 and RCP 8.5 respectively (Hare, 2003). For this climate condition, the first rainfall season MAM will register higher mean compared to the second rainfall season SON under both RCP 4.5 and RCP 8.5.

Table 6.17: Projected change in seasonal and annual rainfall total under Cool-wet regime for RCP 4.5 and RCP 8.5 in Nakapiripirit station from (2025 to 2040)

Scenario	Cool-wet RCP 4.5					Cool-wet RCP 8.5				
s										
Statistics	DJF	MA M	JJA	SON	Annua l	DJF	MA M	JJA	SON	Annua l
Mean	137.56	465.69	536.66	356.34	1496.24	210.47	357.04	382.20	309.62	1259.33
Standard deviation	66.40	93.22	90.78	89.41	169.37	106.03	75.86	64.55	76.88	167.93
Coefficient of variation	48.27	20.02	16.92	25.09	11.32	50.38	21.25	16.89	24.83	13.33
Change in mean	57.95	97.02	148.90	65.96	369.81	126.77	8.64	- 53.22	- 53.46	28.74

6.5.6 Projected changes in seasonal and annual mean temperature in Sironko catchment between 2025-2040

The change in seasonal and annual mean temperature (T-Mean) in Buginyanya station as projected from 2025 to 2040 relative to baseline period between 1980 and 2009 for Hot-dry and Cool-wet climate regimes under both RCP 4.5 and RCP 8.5 are presented in (Table 6.18-6.19). Accordingly, Table 6.18 indicates increasing seasonal and annual mean temperature for a Hot-dry climate regime under both RCP 4.5 and RCP 8.5 respectively. Relative to baseline period, SON is the coolest season and DJF is the warmest dry season (Table 6.18). The change in T-mean ranged from 2.30 °C in SON to 3.96 °C in DJF and 2.71°C in MAM to 3.40 °C in JJA under RCP 4.5 and RCP 8.5 respectively.

Table 6.18: Projected changes in seasonal and annual mean temperature under Hot-dry regime and RCP 4.5 and RCP 8.5 in Buginyanya station from 2025 to 2040

Scenarios		Hot-dry RCP 4.5					Hot-dry RCP 8.5				
Statistics	DJF	MA M	JJA	SON	Annua l		DJF	MA M	JJA	SON	Annua l
Average	27.97	26.1	24.13	25.13	25.82		27.09	26.50	25.31	25.76	26.16
Standard deviation	0.62	0.83	0.84	0.79	0.69		1.06	1.20	0.90	0.99	0.97
Coefficient of variation	2.23	3.16	3.46	3.15	2.66		3.91	4.52	3.55	3.84	3.72
Change in mean	3.96	2.6	2.39	2.3	2.81		2.91	2.71	3.40	3.13	3.04

Similarly, Table 6.19 indicates increase in seasonal and annual mean temperature in Buginyanya station between 2025 and 2040 considering a Cool-wet climate regime under both RCP 4.5 and RCP 8.5 respectively. Again, SON is the coolest rainfall season and DJF is the warmest dry season with the change in T-mean ranging from 0.53 °C in SON to 0.97 °C in JJA and 2.38 °C in DJF to 3.20 °C in JJA under RCP 4.5 and RCP 8.5 respectively.

Table 6.19: Projected changes in seasonal and annual mean temperature under Cool-wet regime and RCP 4.5 and RCP 8.5 in Buginyanya station between 2025 and 2040

Scenarios		Cool-wet RCP 4.5					Cool-wet RCP 8.5				
Statistics	DJF	MA M	JJA	SON	Annua l		DJF	MA M	JJA	SON	Annua l
Mean	24.76	24.7	22.88	23.16	23.87		26.56	26.74	25.11	25.03	25.85
Standard deviation	1.06	1.2	0.9	0.99	0.97		1.06	1.20	0.90	0.99	0.97
Coefficient of variation	4.27	4.85	3.93	4.27	4.08		3.99	4.48	3.58	3.95	3.76
Change in mean	0.58	0.91	0.97	0.53	0.75		2.38	2.95	3.20	2.40	2.73

In Kumi station like it was in Buginyanya station, all GCMs projected increasing annual T-Mean under both RCP 4.5 and RCP 8.5 Table 6.20 for a Hot-dry climate regime. Seasonal T-Mean is

projected to increase in the range of 0.07 °C in DJF to 1.18°C under RCP 4.5 and 2.74 °C in MAM to 3.55 °C in JJA under RCP 8.5, respectively. Under this climate regime, JJA will be the warmest season under RCP 4.5 while DJF will be the coolest season under RCP 8.5, respectively between 2025 and 2040.

Table 6.20: Projected changes in seasonal and annual mean temperature under Hot-dry regime and RCP 4.5 and RCP 8.5 in Kumi station from 2025 to 2040

Scenarios	Hot-dry RCP 4.5					Hot-dry RCP 8.5				
Statistics	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual
Mean	27.28	26.69	24.66	25.36	25.99	29.18	28.37	27.02	27.83	28.09
Standard deviation	0.64	0.76	0.54	0.61	0.47	0.64	0.76	0.54	0.61	0.47
Coefficient of variation	2.34	2.84	2.20	2.40	1.81	2.19	2.68	2.00	2.18	1.67
p-value of trend	0.24	0.95	0.86	0.48	0.90	0.24	0.95	0.86	0.48	0.90
Change in mean	1.07	1.06	1.18	0.72	1.01	2.97	2.74	3.55	3.19	3.11

Under Cool-wet climate regime in Kumi, seasonal mean temperature will increase in the range of 0.59 °C in SON to 1.11 °C in JJA under RCP 4.5 while it will increase in the range of 2.04 °C in MAM to 2.38 °C in DJF under RCP 8.5 respectively (Table 6.21). Therefore, DJF is expected to be the coolest season in Kumi under RCP 4.5 while DJF is expected to be the warmest season under RCP 8.5 for a Cool-wet climate regime.

Table 6.21: Projected changes in seasonal and annual mean temperature under Cool-wet regime and RCP 4.5 and RCP 8.5 in Kumi station from 2025 to 2040.

Scenarios	Cool-wet RCP 4.5					Cool-wet RCP 8.5				
Statistics	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual
Mean	26.85	26.57	24.59	25.23	25.80	28.60	27.67	25.99	26.73	27.24
Standard deviation	0.64	0.76	0.54	0.61	0.47	0.64	0.76	0.54	0.61	0.47
Coefficient of variation	2.38	2.86	2.20	2.41	1.82	2.23	2.74	2.08	2.27	1.73
p-value of trend	0.24	0.95	0.86	0.48	0.90	0.24	0.95	0.86	0.48	0.90
Change in mean	0.63	0.94	1.11	0.59	0.82	2.38	2.04	2.51	2.09	2.26

Projected change in seasonal mean temperature in Nakapiripirit stations between 2025 and 2040 points in the positive end considering a Hot-dry climate regime under both RCP 4.5 and RCP 8.5 (Table 6.22). Between 2025 and 2040, T-mean in Nakapiripirit station is projected to increase in the range of 0.75 °C in SON and 1.18 °C in DJF under RCP 4.5 and 2.30 °C in SON to 3.96 °C in DJF under RCP 4.5 to 4.5 °C under RCP 8.5 respectively. Projected relative changes in T-Max, T-Min, and T-Max were generally below 4 °C for all the models in Nakapiripirit.

Table 6.22: Projected changes in seasonal and annual mean temperature under Hot-dry regime and RCP 4.5 and RCP 8.5 in Nakapiripirit station from 2025 to 2040

Scenarios	Hot-dry RCP 4.5					Hot-dry RCP 8.5				
Statistics	DJF	MA M	JJA	SON	Annua l	DJF	MA M	JJA	SON	Annua l
Mean	25.18	24.60	22.82	23.58	24.04	27.97	26.10	24.13	25.13	25.82
Standard deviation	0.62	0.83	0.84	0.79	0.69	0.62	0.83	0.84	0.79	0.69
Coefficient of variation	2.48	3.36	3.66	3.35	2.86	2.23	3.16	3.46	3.15	2.66
p-value	0.19	0.93	0.18	0.22	0.67	0.19	0.93	0.18	0.22	0.67
Change in mean	1.18	1.10	1.08	0.75	1.03	3.96	2.60	2.39	2.30	2.81

Considering a Cool-wet climate regime in Nakakpiripirit, seasonal mean temperature is projected to increase in the range of 0.86 °C in DJF to 1.49 °C in JJA and 3.23 °C in SON and 3.55 °C in MAM under RCP 4.5 and RCP 8.5, respectively between 2025 and 2040 relative to from 1980 to 2009 period (Table 6.23).

Table 6.23 Projected changes in seasonal and annual mean temperature under Cool-wet regime and RCP 4.5 and RCP 8.5 in Nakapiripirit station from 2025 to 2040

Scenarios	Cool-wet RCP 4.5					Cool-wet RCP 8.5				
Statistics	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual
Mean	24.87	24.6	23.2	23.92	24.15	27.25	27.05	25.12	26.07	26.36
Standard deviation	0.62	0.83	0.84	0.79	0.69	0.62	0.83	0.84	0.79	0.69
Coefficient of variation	2.51	3.36	3.59	3.31	2.84	2.29	3.05	3.32	3.03	2.61
p-value of trend	0.19	0.93	0.18	0.22	0.67	0.19	0.93	0.18	0.22	0.67
Change in mean	0.86	1.1	1.49	1.08	1.13	3.24	3.55	3.38	3.23	3.35

Test for significant differences between MAM and SON rainfall during baseline from 1980 to 2009 and in the medium timescale between 2025 and 2040 were carried out using one sample t-test. Result shows no significant different between MAM and SON rainfall during baseline period. However, significant differences were detected between MAM and SON rainfall in Buginyanya station given a Hot-dry climate regime under RCP 4.5, Cool-wet under RCP 4.5 and RCP 8.5; in Kumi station given a Hot-dry climate under RCP 4.5; and in Nakapiripirit station given a Cool-wet climate regime under RCP 8.5 (Table 6.24). Furthermore, significant differences were also detected between MAM rainfall in the medium timescale from 2025 to 2040 and MAM rainfall during baseline period in Buginyanya station given a Cool-wet climate regime under RCP 4.5, Cool-wet climate regime under RCP 4.5 and RCP 8.5; and in Nakapiripirit station considering a Hot-dry climate condition under RCP 8.5. But no significant difference was detected between SON rainfall from 2025 to 2040 compared to SON rainfall during period 1980-2009 except in Kumi station given a Cool-wet climate regime under RCP

8.5. Generally, the differences were about twofold positives which indicate more rainfall in the future scenarios. At this point we reject the Null hypothesis that MAM rainfall have not significantly varied from SON seasonal rainfall in Sironko catchment.

Table 6.24 Test for significant differences between MAM and SON mean rainfall during baseline 1980 to 2009 and in the medium timescale 2025 to 2040

Buginyanya Hot-dry						
	2025-2040		1980-2040		1980-2040	
	MAM (mm)	SON (mm)	MAM (mm)	MAM (mm)	SON (mm)	SON (mm)
RCP 4.5	424.15	372.40	424.15	344.10	372.40	207.50
RCP 8.5	547.38	391.79	547.38	344.10	391.79	207.50
t	15.39	6.04	9.60	4.39	3.52	2.75
p-value	0.04	0.10	0.07	0.14	0.18	0.22
Buginyanya Cool-wet						
RCP 4.5	466.40	444.72	466.40	344.10	444.72	207.50
RCP 8.5	361.13	422.47	361.13	344.10	422.47	207.50
t	42.03	12.78	6.62	41.41	2.75	2.93
p-value	0.02	0.04	0.10	0.02	0.22	0.21
Kumi Hot-dry						
RCP 4.5	388.25	437.56	388.25	431.11	437.56	322.66
RCP 8.5	547.38	391.79	547.38	431.11	391.79	322.66
t	16.75	6.04	19.12	8.42	6.62	10.34
p-value	0.04	0.10	0.03	0.08	0.10	0.06
Kumi Cool-wet						
RCP 4.5	466.14	444.72	466.14	431.11	444.72	322.66
RCP 8.5	459.11	346.49	459.11	431.11	346.49	322.66
t	42.52	7.15	25.61	31.79	6.39	28.08
p-value	0.01	0.09	0.02	0.02	0.10	0.02
Nakapiripirit Hot-dry						
RCP 4.5	339.79	409.98	339.79	368.67	409.98	290.38
RCP 8.5	473.21	373.24	473.21	368.67	373.24	290.38
t	10.68	8.47	24.53	8.05	5.86	8.01
p-value	0.06	0.07	0.03	0.08	0.11	0.08
Nakapiripirit Cool-wet						
RCP 4.5	465.69	356.34	465.69	368.67	356.34	290.38
RCP 8.5	357.04	382.20	347.04	368.67	382.20	298.30
t	7.52	29.38	8.60	62.40	9.80	7.33
p-value	0.08	0.02	0.07	0.01	0.06	0.09

6.5.7 Mann-Kendall trends and Sen's slope estimates of projected seasonal rainfall in Sironko catchment between 2025 and 2040

The Mann-Kendall trends and Sen's slope estimates of projected seasonal rainfall in Sironko catchment between 2025 and 2040 under Cool-wet and Hot-dry climate regimes for RCP 4.5 and RCP 8.5 are presented in (Table 6.25 and 6.26). Projected rainfall in Buginyanya station shows under Cool-wet climate regime suggest increasing trends under both RCP 4.5 and RCP 8.5 (Table 6.25). However, the trends are not statistically significant. The increase in MAM total rainfall ranges from 1.34 mm per year to 1.50 mm per year under RCP 4.5 and RCP 8.5 while for SON it ranged from 0.86mm/year to 0.23mm/year under RCP 4.5 and RCP 8.5 for the Cool-wet climate regime.

Table 6.25 Mann-Kendall trends and Sen's slope estimates of projected seasonal rainfall in Buginyanya station between 2025 and 2040 under Cool-wet regime for RCP 4.5 and RCP 8.5

Scenarios		RCP 4.5			RCP 8.5		
Time series	Test Z	Q (mm)	p-value	Test Z	Q (mm)	p-value	
DJF	1.22	2.74	0.31	0.86	3.87	0.39	
MAM	0.32	1.34	0.71	0.32	1.50	0.77	
JJA	0.50	2.70	0.95	0.41	1.65	0.99	
SON	0.23	0.86	0.90	-0.05	0.23	0.97	

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

Similarly, under Hot-dry climate condition, seasonal rainfall in Buginyanya will increase between 2025-2040 for both RCP 4.5 and RCP 8.5 but the trends are not statistically significant (Table 6.26). Under this climatic condition, MAM rainfall will increase in the range of 1.34 mm to 1.82 mm under RCP 4.5 and RCP 8.5 respectively. At the same time SON rainfall will increase in the range from 0.86 mm under RCP 4.5 to 0.99 mm under RCP 8.5

Table 6.26: Mann-Kendall trends and Sen's slope estimates of projected seasonal rainfall in Buginyanya station from 2025 to 2040 under Hot-dry climate regime for RCP 4.5 and RCP 8.5

Scenarios		RCP 4.5			RCP 8.5		
Time series	Test Z	Q (mm)	p-value	Test Z	Q (mm)	p-value	
DJF	1.22	2.74	0.36	1.04	2.63	0.31	
MAM	0.32	1.34	0.75	0.41	1.82	0.76	
JJA	0.5	2.70	0.91	0.50	2.42	0.90	
SON	0.23	0.86	0.82	0.23	0.99	0.77	

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

For Kumi station under Cool-wet climatic condition, seasonal rainfall will increase except for SON under RCP 8.5. However, both trends increasing and decreasing are not significant (Table 6.27). MAM rainfall will increase by 1.37 mm under RCP 4.5 to 1.50 mm under RCP 8.5 while SON rainfall will decrease by 0.23 mm under RCP 8.5.

Table 6.27: Mann-Kendall trends and Sen's slope estimates of projected seasonal rainfall in Kumi station from 2025 to 2040 under Cool-wet regime for RCP 4.5 and RCP 8.5

Scenarios		RCP 4.5			RCP 8.5		
Time series	Test Z	Q (mm)	p-value	Test Z	Q (mm)	p-value	
DJF	1.17	3.20	0.31	0.86	3.87	0.39	
MAM	0.50	1.37	0.69	0.32	1.50	0.76	
JJA	0.59	3.87	0.87	0.41	1.65	0.99	
SON	0.00	0.00	0.78	-0.05	-0.23	0.97	

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

Considering Hot-dry climate regime in Kumi from 2025 to 2040, it is seen from Table 6.28 that seasonal rainfall will increase for both RCP 4.5 and RCP 8.5. However, SON rainfall will decrease by 1.06 mm though both the increasing and decreasing trends are not significant.

Table 6.28: Mann-Kendall trends and Sen's slope estimates of projected seasonal rainfall in Kumi station between 2025 and 2040 under Hot-dry climate regime for RCP 4.5 and RCP 8.5

Scenarios		RCP 4.5			RCP 8.5		
Time series	Test Z	Q (mm)	p-value	Test Z	Q (mm)	p-value	
DJF	1.22	2.74	0.36	1.31	5.17	0.31	
MAM	0.32	1.34	0.33	0.32	2.41	0.81	
JJA	0.50	2.70	0.91	0.50	1.93	0.94	
SON	0.23	0.86	0.82	-0.14	-1.06	0.9	

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

In Nakapiripirit, the results show that only SON rainfall will decrease under Cool-wet condition for RCP 4.5. Otherwise, both the increasing and decreasing trends are not statistically significant under both RCPs (Table 6.29).

Table 6.29: Mann-Kendall trends and Sen's slope estimates of projected seasonal rainfall in Nakapiripirit station between 2025 and 2040 under Cool-wet regime for RCP 4.5 and RCP 8.5

Scenarios		RCP 4.5			RCP 8.5		
Time series	Test Z	Q (mm)	p-value	Test Z	Q (mm)	p-value	
DJF	1.13	5.03	0.10	1.40	7.63	0.18	
MAM	0.41	2.43	0.28	0.50	3.34	0.32	
JJA	0.32	3.12	0.89	0.00	0.45	0.77	
SON	0.00	-0.04	0.69	0.05	0.31	0.65	

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

Similarly, for Hot-dry condition only SON rainfall will decrease for both RCP 4.5 and RCP 8.5 but both the increasing trends for DJF, MAM, JJA and decreasing trend for SON are not significant (Table 6.30).

Table 6.30: Mann-Kendall trends and Sen's slope estimates of projected seasonal rainfall in Nakapiripirit station from 2025 to 2040 under Hot-dry climate regime for RCP 4.5 and RCP 8.5

Scenarios		RCP 4.5			RCP 8.5		
Time series	Test Z	Q (mm)	p-value	Test Z	Q (mm)	p-value	
DJF	1.13	6.78	0.12	1.22	9.80	0.19	
MAM	1.04	3.29	0.28	0.68	1.97	0.45	
JJA	0.32	3.83	0.86	0.18	2.56	0.89	
SON	-0.14	-0.95	0.81	-0.23	-1.20	0.83	

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

From above, seasonal rainfall across Sironko catchment showed both increasing and decreasing trends. However, both trends (increasing or decreasing) are not significant. Therefore, the Null hypothesis that SON seasonal rainfall in Sironko catchment is not going to significantly change in the future scenarios is accepted.

6.5.8 Mann-Kendall trends and Sen's slope estimates of projected seasonal mean temperature in Sironko catchment between 2025-2040

The Mann-Kendall trends and Sen's slope estimates of projected seasonal and annual mean temperature for Cool-wet and Hot-dry climate regimes under RCP 4.5 and RCP 8.5 in Sironko catchment between 2025 and 2040 are presented in Table 6.31 and 6.32. It is seen from DJF and MAM seasons' mean temperature in Buginyanya station from 2025 to 2040 under Cool-wet climate will increase at ($p = 0.03$) and ($p = 0.04$) levels of significant for both RCP 4.5 and RCP 8.5 as indicated in Figure 6.13 and Figure 6.14, respectively. For the same period, JJA and SON mean temperatures will decrease but the trends are not significant under both RCP 4.5 and RCP 8.5.

Table 6.31: Mann-Kendall trends and Sen's slope estimates of projected seasonal mean temperature for Cool-wet climate regime under RCP 4.5 and RCP 8.5 in Buginyanya from 2025 to 2040

Scenarios	RCP 4.5			RCP 8.5		
Time series	Test Z	Q	p-value	Test Z	Q	p-value
DJF	2.21*	0.07	0.03	2.21*	0.07	0.03
MAM	2.12*	0.08	0.04	2.12*	0.08	0.04
JJA	-0.86	-0.03	0.21	-0.86	-0.03	0.21
SON	-0.05	-0.01	0.28	-0.05	-0.01	0.28

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

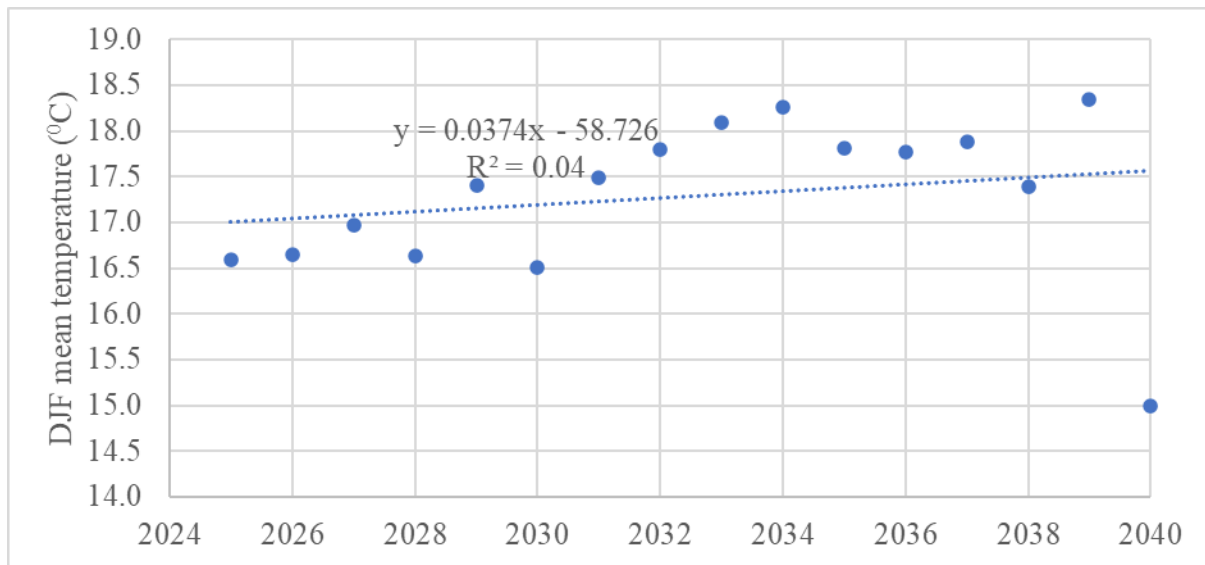


Figure 6.13: Scatter plots for DJF mean temperature in Buginyanya station from 2025 to 2040 period under Cool-wet regime, RCP 4.5

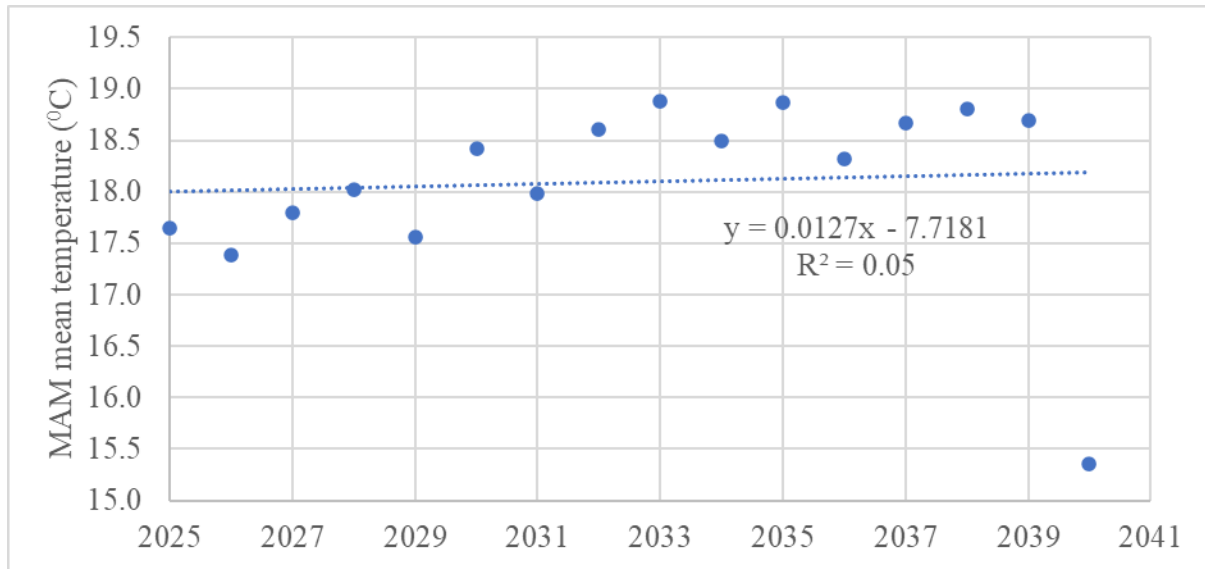


Figure 6.14: Scatter plots for MAM mean temperature in Buginyanya station from 2025 to 2040 under Cool-wet regime, RCP 4.5

Similarly, for a Hot-dry climate regime in Buginyanya station from 2025 to 2040, DJF and MAM mean temperatures will both increase at ($p = 0.03$) and ($p = 0.04$) levels of significant under RCP 4.5 and RCP 8.5, respectively. On the other hand, JJA and SON mean temperature will increase for the same period. However, the trends are not significant (Table 6.32).

Table 6.32: Mann-Kendall trends and Sen's slope estimates of projected seasonal mean temperature for Hot-dry climate regime under RCP 4.5 and RCP 8.5 in Buginyanya from 2025 to 2040

Scenarios		RCP 4.5		RCP 8.5		
Time series	Test Z	Q	p-value	Test Z	Q	p-value
DJF	2.21*	0.07	0.03	2.21*	0.07	0.03
MAM	2.12*	0.08	0.04	2.12*	0.08	0.04
JJA	-0.86	-0.03	0.21	-0.86	-0.03	0.21
SON	-0.05	-0.01	0.28	-0.05	-0.01	0.28

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

Seasonal mean temperature in Kumi station under Cool-wet climate regime between 2025 and 2040 shows that both DJF and MAM mean temperatures will increase but the trend is only

significant ($p = 0.02$) for DJF under both RCP 4.5 and RCP 8.5 (Table 5.33). On the other hand, JJA and SON mean temperatures are projected to decrease in the same period. However, the trends are not significant under both RCP 4.5 and RCP 8.5.

Table 6.33: Mann-Kendall trends and Sen's slope estimates of projected seasonal mean temperature for Cool-wet climate regime under RCP 4.5 and RCP 8.5 in Kumi between 2025 and 2040

Scenarios		RCP 4.5		RCP 8.5		
Time series	Test Z	Q	p-value	Test Z	Q	p-value
DJF	2.23*	0.09	0.02	2.30*	0.09	0.02
MAM	1.49	0.05	0.95	1.49	0.05	0.95
JJA	-0.05	0.00	0.86	-0.05	0.00	0.86
SON	-0.13	-0.03	0.48	-1.13	-0.03	0.48

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

Given a Hot-dry climate between 2025 and 2040, mean temperatures in Kumi stations for DJF and MAM seasons will increase. However, the trend is only significant ($p = 0.02$) for DJF under both scenarios. Similarly, both JJA and SON showed declining but not significant trends in mean temperatures from 2025 to 2040 under both RCP 4.5 and RCP 8.5, respectively (Table 6.34).

Table 6.34: Mann-Kendall trends and Sen's slope estimates of projected seasonal mean temperature for Hot-dry climate regime under RCP 4.5 and RCP 8.5 in Kumi from 2025 to 2040

Scenarios		RCP 4.5		RCP 8.5		
Time series	Test Z	Q	p-value	Test Z	Q	p-value
DJF	2.30*	0.09	0.02	2.30*	0.09	0.02
MAM	1.49	0.05	0.95	1.49	0.05	0.95
JJA	-0.05	0.00	0.86	-0.05	0.00	0.86
SON	-1.13	-0.03	0.48	-1.13	-0.03	0.48

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

Given a Cool-wet climate in Nakapiripirit station between 2025 and 2040, Table 6.35 indicates that both DJF and MAM mean temperatures will increase. However, the trend is only significant ($p = 0.01$) for DJF under both RCP 4.5 and RCP 8.5, respectively. In the same way, both JJA and

SON mean temperatures will decrease under RCP 4.5 and RCP 8.5 but the trends are not significant.

Table 6.35: Mann-Kendall trends and Sen's slope estimates of seasonal mean temperature for Cool-wet climate regime under RCP 4.5 and RCP 8.5 in Nakapiripirit between 2025 and 2040

Scenarios		RCP 4.5		RCP 8.5		
Time series	Test Z	Q	p-value	Test Z	Q	p-value
DJF	2.03*	0.08	0.01	2.03*	0.08	0.01
MAM	1.85	0.06	0.93	1.85	0.06	0.93
JJA	-0.68	-0.02	0.16	-0.68	-0.01	0.16
SON	-0.59	-0.02	0.22	-0.59	-0.02	0.22

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

For a Hot-dry climate between 2025-2040 in Nakapiripirit station, it is seen from Table 6.36 that both DJF and MAM seasons mean temperature will increase under both RCP 4.5 and RCP 8.5, respectively. Then trends are significant ($p = 0.01$) for DJF under both RCPs while for MAM, the trend is only significant ($p = 0.04$) under RCP 8.5. On the other hand, JJA and SON mean temperatures will decrease under both RCP 4.5 and RCP 8.5 but the trends are not significant.

Table 6.36: Mann-Kendall trends and Sen's slope estimates of seasonal mean temperature for Hot-dry climate regime under RCP 4.5 and RCP 8.5 in Nakapiripirit between 2025 and 2040

Scenarios		RCP 4.5		RCP 8.5		
Time series	Test Z	Q	p-value	Test Z	Q	p-value
DJF	2.03*	0.08	0.01	2.03*	0.08	0.01
MAM	1.85	0.06	0.93	1.85*	0.06	0.04
JJA	-0.68	-0.01	0.16	-0.68	-0.01	0.16
SON	-0.59	-0.02	0.22	-0.59	-0.02	0.22

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

6.5.9 Mann-Kendall trends and Sen's slope estimates of projected annual T-Mean, and total rainfall in Sironko catchment for the period (2025-2040)

All GCMs projected increasing but not significant annual rainfall in Buginyanya station under both RCP 4.5 and RCP 8.5 between 2025 and 2040 (Table 6.37). The mean annual total rainfall is projected to increase in the range of 1.82 mm to 8.11 mm under RCP 4.5 and 1.17 mm to 13.16 mm under RCP 8.5, respectively. Similarly, all GCMs suggest statistically significant increase in annual mean temperature for both RCP 4.5 and RCP 8.5. For example, the regimes that showed significant trends in mean temperature under RCP 4.5 are: (Cool-wet); (Hot-wet); (Cool-dry); (Hot-dry); and (Middle) respectively. Under RCP 8.5 the GCMs that showed significant trends in T-Mean were: (Cool-wet); (Hot-wet); (Cool-dry); (Hot-dry); and (Middle) respectively. The increase in T-Mean is consistent at 0.08 °C and 0.05 °C for RCP 4.5 and RCP 8.5, respectively.

Table 6.37: Mann-Kendall trends and Sen's slope estimates of annual mean temperature and total rainfall in Buginyanya station between 2025 and 2040 under RCP 4.5 and RCP 8.5

Scenarios	RCP 4.5			RCP 8.5			
Annual time series	Z	Q	p-value	Time series	Z	Q	p-value
T-Mean (Cool/wet)	3.56	0.05*	0.00	T-Mean (Cool/wet)	3.56	0.05*	0.00
Rainfall (Cool/wet)	0.08	1.82	0.36	Rainfall (Cool/wet)	0.00	1.17	0.48
T-Mean (Hot/wet)	3.56	0.05*	0.00	T-Mean (Hot/wet)	3.56	0.05*	0.00
Rainfall (Hot/wet)	0.15	3.04	0.40	Rainfall (Hot/wet)	0.23	2.10	0.48
T-Mean (Cool/dry)	3.56	0.05*	0.00	T-Mean (Cool/dry)	3.56	0.05*	0.00
Rainfall (Cool/dry)	0.38	8.11	0.37	Rainfall (Cool/dry)	0.30	2.13	0.37
T-Mean (Hot/dry)	3.56	0.05*	0.00	T-Mean (Hot/dry)	0.36	0.05*	0.00
Rainfall (Hot/dry)	0.30	5.99	0.38	Rainfall (Hot/dry)	0.30	5.99	0.38
T-Mean (Middle)	3.56	0.08*	0.00	T-Mean (Middle)	0.31	0.08*	0.00
Rainfall (Middle)	0.30	4.96	0.39	Rainfall (Middle)	0.91	13.16	0.24

Q = Sen's slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

In Kumi station just like in Buginyanya station, all GCMs projected increasing trends in annual total rainfall and mean temperature under both RCP 4.5 and RCP 8.5, respectively (Table 6.38).

The trend of annual total rainfall is only significance for (Cool/dry) under RCP 8.5 scenarios. The increase in annual total rainfall ranges from 12.49 mm to 17.23 mm per year under RCP 4.5 and from 11.34 mm to 16.96 mm under RCP 8.5. Mean temperatures on the other hand is projected to increase at $p < 0.05$ level of significance under RCP 4.5 and RCP 8.5, respectively. All the models showed a consistent 0.08°C and 0.04°C increase in mean temperature for both RCP 4.5 and RCP 8.5.

Table 6.38: Mann-Kendall tends and Sen's slope estimates of annual mean temperature and total rainfall for Kumi station between 2025 and 2040

Scenarios	RCP 4.5			RCP 8.5			
Annual time series	Z	Q	p-value	Time series	Z	Q	p-value
T-Mean (Cool/wet)	2.80	0.04*	0.00	T-Mean (Cool/wet)	2.73	0.04*	0.00
Rainfall (Cool/wet)	1.36	13.38	0.10	Rainfall (Cool/wet)	1.36	14.60	0.09
T-Mean (Hot/wet)	2.73	0.04*	0.00	T-Mean (Hot/wet)	2.80	0.04*	0.00
Rainfall (Hot/wet)	1.67	12.94	0.05	Rainfall (Hot/wet)	1.29	12.62	0.08
T-Mean (Cool/dry)	2.73	0.04*	0.00	T-Mean (Cool/dry)	2.80	0.04*	0.00
Rainfall (Cool/dry)	1.44	17.23	0.07	Rainfall (Cool/dry)	1.67	16.96*	0.04
T-Mean (Hot/dry)	2.73	0.04*	0.00	T-Mean (Hot/dry)	2.80	0.04*	0.00
Rainfall (Hot/dry)	1.44	17.22	0.07	Rainfall (Hot/dry)	1.36	11.34	0.08
T-Mean (Middle)	2.73	0.04*	0.00	T-Mean (Middle)	2.73	0.04*	0.00
Rainfall (Middle)	1.36	12.49	0.06	Rainfall (Middle)	1.74	14.36	0.06

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

Furthermore, in Nakapiripirit station Table 6.39, all the GCMs projected increasing trends in annual total rainfall and mean temperature for both RCP 4.5 and RCP 8.5. The trends in rainfall were both significant and no significant depending on the GCMs and scenarios as seen from (Table 6.39). The projected increase in annual total rainfall is in the range of 12.47 mm to 20.37 mm under RCP 4.5 and 11.50 mm to 17.25 mm under RCP 8.5, respectively. Similarly, (Cool-

wet); (Hot-wet); (Cool-dry); (Hot-dry) and (Middle) projected increase in annual average mean temperature at $p < 0.05$ level of significance under RCP 4.5. Similarly, (Cool-wet); (Hot-wet); (Cool-dry); (Hot-dry); and (Middle) projected an increase in average annual mean temperature in Nakapiripirit station at $p < 0.05$ level of significance under RCP 8.5, respectively. All GCMs projected annual increase of 0.06°C for in mean temperature under both RCP 4.5 and 8.5.

Table 6.39: Mann-Kendall tends and Sen's slope estimates of projected annual mean temperature and total rainfall for Nakapiripirit station between 2025 and 2040

Scenarios	RCP 4.5			RCP 8.5			
Annual time series	Z	Q	p-value	Time series	Z	Q	p-value
T-Mean (Cool/wet)	3.18	0.06*	0.00	T-Mean (Cool/wet)	3.18	16.70*	0.00
Rainfall (Cool/wet)	2.35	14.58*	0.03	Rainfall (Cool/wet)	2.05	0.03	0.05
T-Mean (Hot/wet)	3.18	0.06*	0.00	T-Mean (Hot/wet)	3.18	17.25*	0.00
Rainfall (Hot/wet)	1.89	19.27	0.08	Rainall (Hot/wet)	1.89	0.03*	0.04
T-Mean (Cool/dry)	3.18	0.06*	0.00	T-Mean (Cool/dry)	3.18	13.88*	0.00
Rainfall (Cool/dry)	2.35	12.47*	0.03	Rainfall (Cool/dry)	1.89	0.03*	0.04
T-Mean (Hot/dry)	3.18	0.06*	0.00	T-Mean (Hot/dry)	3.18	14.54*	0.00
Rainfall (Hot/dry)	2.12	20.37*	0.02	Rainfall (Hot/dry)	1.12	0.03*	0.04
T-Mean (Middle)	3.18	0.06*	0.00	T-Mean (Middle)	3.18	11.50*	0.00
Rainfall (Middle)	1.74	12.88	0.05	Rainfall (Middle)	1.74	0.03*	0.04

Q = Sens' slope marked * if trend at $\alpha = 0.05$ or $p < 0.05$ level of significance

6.6 Discussion of the results

6.6.1 Variability in rainfall, temperature, and river flow in Sironko catchment

Based on observational rainfall and temperature data from UNMA and stream flow data from MWE, the variability in rainfall, temperature and river flow were assessed in Sipi sub-catchment of Sironko from 1981-2015. The results revealed inter-seasonal variation in mean rainfall across the sub-catchment, with SON rainfall varying more than MAM rainfall. According to (Hare,

2003), SON mean rainfall across the entire sub-catchment is categorized as highly variable $CV > 30$, whereas MAM rainfall is grouped under less variable $CV < 20$ or moderately variable $20 < CV < 30$. However, the mean of rainfall in MAM and SON for Buginyanya, Kapchorwa, and the mean of rainfall over the sub-catchment have not varied much. This suggests that the inter-seasonal variabilities could be a result of extreme events, as depicted by the SPIs. In fact, Bomuhangi et al. (2016) also found variations in the amount of annual and seasonal rainfall in the greater Mt. Elgon region between 1993 and 2013. Looking at the results on seasonal and annual rainfall variabilities from the perspective of water availability, Sipi sub-catchment gets, on average, an equal amount of water in both the MAM and SON seasons. However, results depict high river flows in the catchment during the SON season as compared to MAM. The observed patterns of monthly rainfall and river flows can be attributed to many factors, including the following: (a) the development of the tropical cyclone during December, January, and February (DJF); (b) the influence of the El Nino Southern Oscillation (ENSO); (c) during that period, the region had gone through a long dry season (DJF) where the volume of most rivers was reduced due to high evaporation and low rainfall. According to Oriangi (2019), the climate of Uganda is influenced by the Inter-Tropical Convergence Zone (ITCZ), varied relief, geo-location, and inland lakes. In the second rainfall season, the flow pattern pick-up, together with the rainfall, reaches its peak, which is more than the peak of the second rainfall season. This can be attributed to accumulation of water in the river and ground during the first rainfall season. The pattern also indicates no major abstractions of water from the river. Results of seasonal and annual variabilities therefore point out that water is available (in terms of quantity) in the soil in both MAM and SON rainfall season and in the river throughout the year.

Over the entire Sironko catchment, variability in rainfall and temperature was assessed both in the baseline and future scenarios under RCP 4.5 and RCP 8.5 for five climate regimes Cool-wet, Cool-dry, Hot-wet, Hot-dry and Middle respectively. The results as it were in Sipi sub-catchment, revealed inter-seasonal and inter-annual variations in both rainfall and mean temperature across Sironko catchment. Generally, DJF rainfall across the Sironko catchment both during baseline period from 1980 to 2009 and in the near future from 2025 to 2040 under both RCP 4.5 and RCP 8.5 are more variable than the other seasons. The first rainfall season MAM has been more stable than the second rainfall season SON both in the baseline period and the near future 2025-2040. It is important to note that MAM rainfall in Kumi and Nakapiripirit

will be less than baseline MAM rainfall for the respective stations under RCP 4.5 for a Cool-wet climate regime. On the other hand, JJA rainfall in Kumi station between 2025 and 2040 for both Cool-wet and Hot-dry climate conditions under RCP 8.5 will also be less than JJA rainfall during baseline period. In Nakapiripirit meanwhile, both JJA and SON rainfall under RCP 8.5 for Cool-wet climate regime will be less than the corresponding JJA and SON rainfall for baseline period.

Mean temperature variations both during baseline from 1980 to 2009 and in the near future from 2025 to 2040 is highest in Buginyanya and Nakapiripirit stations, respectively. The station with the least mean temperature variation is Kumi. The temperature pattern still agrees with the fundamental fact in Geography that the higher you go the cooler it becomes (Ohmura, 2012; Sanroma et al., 2010). Another possible explanation to the temperature pattern could also be due to cloud effects in the Mountain stations Buginyanya and Nakapiripirit (Ohmura, 2012; Sanroma et al., 2010). On the other hand, Kumi station is located in the plain and therefore has less clouds cover hence, a stable temperature pattern

The results show that SON and DJF seasonal rainfall can generally categorized as highly variable $CV > 30$, for both baseline period and in the near future from 2025 to 2040 across the entire catchment (Hare, 2003). Similarly, MAM rainfall both for baseline period and in the near future can generally be grouped under less variable $20 < CV$ or moderately variable $20 < CV < 30$. However, MAM total rainfall in Kumi and Nakapiripirit stations are projected from 2025 to 2040 to be less than that of baseline/from 1980-2009 for both RCP 4.5 and RCP 8.5, respectively. The inter-seasonal and inter annual variability in rainfall could be a result of extreme events (Luwa et al., 2021). Bomuhangi et al. (2016) also found variations in the amount of annual and seasonal rainfall in the greater Mt. Elgon region between 1993 and 2013.

The observed patterns seasonal and annual rainfall can be attributed to many factors, including the following: (a) the development of the tropical cyclone during December, January, and February (DJF); (b) the influence of the El Nino Southern Oscillation (ENSO); (c) during that period, the region goes through a long dry season (DJF). According to Oriangi (2019), the climate of Uganda is influenced by the Inter-Tropical Convergence Zone (ITCZ), varied relief, geo-location, and inland lakes. Looking at the results on seasonal and annual rainfall variabilities from the perspective of water availability, Sironko catchment is projected to get on average,

more rainfall under both RCP 4.5 and RCP 8.5. Agricultural extension officers could therefore use this finding to advise farmer to maximize production in the MAM season which is more stable than SON season.

6.6.2 Trends and magnitudes of seasonal and annual variability in rainfall and temperature and river flow in Sironko catchment

At a sub-catchment scale the result showed that both annual flow and minimum temperature have increased significantly but annual mean rainfall did not increase significantly. Although result suggests water availability in the catchment throughout the years, the finding presents both opportunities and challenges to water resources management in the future. The opportunity that presents itself is that the Sipi sub-catchment has the potential for irrigation agriculture to support food production even in times of droughts and, hence, increased productivity. However, irrigation agriculture has been associated with intensification and high applications of fertilizers and other agrochemicals that are bound to exacerbate non-point pollution of water resources in the sub-catchment (Chen et al., 2020; Kourgialas et al., 2017). Therefore, future policy in favor of irrigated agriculture in Sironko catchment should also have a deliberate side for balancing the tradeoff between production and ecosystem health.

The findings also suggest that the limiting factor for crop production in the Sipi sub-catchment in the two rainfall seasons is not water but could be the variation in temperature. Different crops are known to respond differently to small differences in temperature which may have a direct link to sunshine hours'/day length (Benedict, 1940). Such variation may affect the flowering patterns and may lead to delayed or early maturity in fruits Sawan, (2018) and Wang et al. (2019), which may also exacerbate pre and post-harvest losses. Similarly, little difference in temperature may provide ambient conditions for pest and diseases (Mubiru et al., 2018) and hence leading to pre- and postharvest loss or reduced crop yields. In Mt. Elgon, Kagezi et al. (2018) reported significant increase in the incidence of coffee leaf miners (CLM) with increasing altitude. The authors linked the result to variation of rainfall and ambient temperatures which affect the coffee plant and thus, the pest and its natural enemies. A study by Mwaura & Okoboi, (2014) found that variation in rainfall and temperature from the long-term mean has significant effects on crop output, while an exponential increase in rainfall has detrimental effect on crop output. In the study by Mubiru et al. (2018), local farmers in Rakai and Hoima districts in Western Uganda

reported erratic rainfall onset and cessation, poor seasonal distribution of rainfall and decreased rainfall, variations in temperatures, drought, increasing disease and pest incidences, decreasing water sources, lack of pasture, bush fires, hailstorms, and changes in crop flowering and fruiting times as the major climate-related risks being experienced.

At a catchment scale trend analysis showed that both seasonal and annual rainfall have increased from 1980 to 2009 and will continue to increase between 2025 and 2040 except for SON in Buginyanya station for a Cool-wet climate and RCP 4.5; SON in Kumi station for a Cool-wet regime and RCP 8.5 and for a Hot-dry regime under RCP 4.5; and in Nakapiripirit given a Cool-wet climate condition under RCP 4.5 given a Hot-dry climate regime under both RCP 4.5 and RCP 8.5, respectively. The increasing and decreasing trends of seasonal rainfall in the future are however, not significant while annual rainfall showed both significant and non-significant increase trends depending on the station, scenario, and regime. Seasonal mean temperatures for DJF and MAM seasons meanwhile have been projected to increase at ($p < 0.05$) across Sironko catchment under both RCP 4.5 and RCP 8.5. Likewise, JJA and SON mean temperatures are projected to decrease at non-significant trends across the Sironko catchment irrespective of the regime and RCPs.

On annual scale, the projected climate of Sironko catchment indicates an increase in annual total rainfall and mean temperature of different magnitudes in all the stations for different GCMs and climate regimes. Noticeable differences between and within stations have also been detected. These differences are expected due to reasons such as differences in GCMs and between the scenarios themselves. For example, all GCMs projected increase in annual total rainfall in all the stations for both RCP 4.5 and RCP 8.5. However, the increase was not statistically significant in Buginyanya station. This finding agrees with a report by UNDP (2013) that revealed no significant trend in rainfall for Mbale region between 2011 and 2040.

The differences among the GCMs and among the scenarios themselves can be seen in Nakapiripirit station under RCP 4.5 where, CESM1-BGC (Cool-wet); MIROC-ESM (Cool-dry); and FGOALS-g2 (Hot-dry) projected significant increase in annual total rainfall at $p < 0.05$ level of significance. Similarly, under RCP 8.5, CanESM2 (Hot-wet); MPI-ESM-LR (Cool-dry); FGOALS-g2 (Hot-dry); and CMCC-CM (Middle) were the GCMs that projected significant

increase in annual rainfall in Nakapiripirit station between 2025-2040. On the other hand, in Kumi station, only bcc-csm-1-1 (Cool-dry) projected significant increase in annual rainfall between 2025 and 2040 under RCP 8.5.

Such inter model differences in projecting future rainfall has also been reported in Uganda by (USAID, 2013) and elsewhere by (Mekonnen & Disse, 2018). The projected significant increase in annual rainfall in Kumi and Nakapiripirit contradicts Hulme et al. (2001) who reported no significant increase in annual rainfall over the entire Uganda for the period 2020-2080. Similar trend in annual rainfall was reported by World Bank (2020) in Uganda. The projected significant increase in annual total rainfall in Nakapiripirit and Kumi stations and no significant increase in annual total rainfall in Buginyanya confirms what was reported by UNDP (2013) that changes in rainfall was not uniform in both space and time.

This result generally suggests that in the medium timescale between 2025 and 2040, water will most likely not be a major limiting factor for agricultural production in the catchment. However, the results present both opportunities and challenges to water resources management in the future. The opportunity that presents itself is that Sironko catchment has the potential for irrigation agriculture to support food production in the medium timescale. However, irrigation agriculture has been associated with intensification and high applications of fertilizers and other agrochemicals that are bound to exacerbate non-point pollution of water resources in the sub-catchment (Chen et al., 2020; Kourgialas et al., 2017). Therefore, future policy in favor of irrigated agriculture in Sironko catchment should also have a deliberate side for balancing the tradeoff between production and ecosystem health.

According to the results, the limiting factors for agricultural production in the medium timescale in Sironko catchment could be the variation in mean temperature. Different crops are known to respond differently to small differences in temperature which may have a direct link to sunshine hours'/day length (Benedict, 1940). Such variation may affect the flowering patterns and may lead to delayed or early maturity in fruits Sawan, (2018) and Wang et al. (2019), which may also exacerbate pre and post-harvest losses. Similarly, little difference in temperature may provide ambient conditions for pest and diseases (Mubiru et al., 2018) and hence leading to pre- and postharvest loss or reduced crop yields. In Mt. Elgon, Kagezi et al. (2018) reported significant increase in the incidence of coffee leaf miners (CLM) with increasing altitude. The authors

linked the result to variation of rainfall and ambient temperatures which affect the coffee plant and thus, the pest and its natural enemies. A study by Mwaura & Okoboi, (2014) found that variation in rainfall and temperature from the long-term mean has significant effects on crop output, while an exponential increase in rainfall has detrimental effect on crop output. In the study by Mubiru et al. (2018), local farmers in Rakai and Hoima districts in Western Uganda reported erratic rainfall onset and cessation, poor seasonal distribution of rainfall and decreased rainfall, variations in temperatures, drought, increasing disease and pest incidences, decreasing water sources, lack of pasture, bush fires, hailstorms, and changes in crop flowering and fruiting times as the major climate-related risks being experienced.

6.7 Conclusions

Thus, this study assessed the trends and magnitude of climate variability and change on a medium timescale in Sironko catchment for the sustainability of livelihoods. Based on the data and methodology as described under section 6.2.2 to 6.2.6 of this chapter, this study concludes that:

1. During baseline (1980-2009) and in the medium timescale 2025-2040, SON seasonal rainfall in Sironko catchment has been/will be highly variable ($CV > 30$) compared to MAM season rainfall which is less variable ($CV < 20$) or moderately variable ($20 < CV < 30$).
2. In the medium timescale 2025-2040, DJF and MAM mean temperatures are projected to increase at ($p < 0.05$) levels of significant across Sironko catchment under both RCP 4.5 and RCP 8.5 and for both Cool-wet and Hot-dry climate regimes. Temperature variation may affect the flowering patterns and may lead to delayed or early maturity in fruits in addition to exacerbating pest and diseases infestations.
3. In the medium timescale 2025-2040, annual rainfall will increase at ($p < 0.05$) levels of significant in Kumi and Nakapiripirit stations under both RCP 4.5 and RCP 8.5 given both Cool-wet or Hot-dry climate regimes. The trends in annual rainfall in Kumi and Nakapiripirit stations present both opportunities and challenges to subsistence agriculture, water resources management, and livelihoods sustainability.

6.8 Recommendations

1. Thus, more studies are required to investigate the effect of increasing temperature on crop production in the catchment.
2. Hence, there is a need to develop capacities of communities within the catchment to better prepare and adapt to anticipate increased rainfall for sustained livelihoods.

CHAPTER SEVEN: IMPACT OF CLIMATE AND LAND USE LAND COVER CHANGES ON THE MAGNITUDE OF SELECTED WATER QUALITY PARAMETERS ON A MEDIUM TIMESCALE IN SIRONKO CATCHMENT

7.1 Abstract

Sironko catchments' population relies on surface water for their water supply and livelihood. This study determined the impact of climate and Land Use Land Cover Change (LULCC) on water quality in Sironko catchment for. Field assessments of selected water quality parameters from January to December 2018 followed standard procedures. The LULCC maps of Sironko catchment 1986, 2000, 2016 and 2040 were developed by maximum likelihoods algorithm of the supervised classification. Baseline 1980-2009 and future scenarios 2025-2040 climate were downscaled by delta method. The climate scenarios and LULCC maps were used to simulate stream flow, total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) loads using the Soil and Water Assessment Tool (SWAT). Mean values of selected water quality parameters in dry and wet seasons were compared with the Uganda National Bureau of Standards (UNBS) guidelines. t-test was employed at $p < 0.05$ level to determine any significant seasonal difference in water quality. Trends and trend magnitudes were determined using the Mann–Kendall trend and Sen's slope estimator. The contribution of climate LULCCs on stream flow, TSS, TN, and TP were computed using a second-degree regression model. Results of LULCC and climate changes are well elaborated in chapter four and five. Regarding selected water quality parameters, fecal coliforms were above UNBS limit for drinking water while seasonal differences were detected at $p < 0.05$ for pH, EC, TP, and DO. Whereas the impacts of both climate and LULCCs on River flow are both significant at $p < 0.05$ levels between 2025 to 2040, climate change will increase River flow and more than land use land cover change while the later will increase TN more than climate change under both RCP 4.5 and RCP 8.5. Future climate and LULCC are likely to worsen water quality pollution in Sironko catchment. Improved sanitation facilities and proper waste management is urgently needed in Sironko catchment.

7.2 Introduction

The impacts of future climate and land use changes on freshwater availability (quantity and quality) are likely to be significant. However, policy discussions and scientific studies have seldomly addressed the important linkages between water quality, climate, and land use changes (IPCC, 2021). Changes in land use and land cover coupled with the impacts of climate change alter river flow through the alternation of overland flow and infiltration, ground water recharge, and flow velocity (Chaturvedi et al., 2021; Mango et al., 2011). These changes amplify nutrients and sediments fluxes in river catchments (Zhang et al., 2013) with serious consequences on ecosystem health and peoples livelihood. For example, floods in mountainous area can cause landslides and drive massive amounts of debris, sediments and other contaminants into water bodies ((Mishra et al., 2021; Torma et al., 2019; Mellander et al., 2018). River siltation due to sedimentation impacts negatively on aquatic habitat and can lead to death of fish and benthic micro-organisms (Ustaoglu & Islam, 2020). Similarly, nutrients enrichment of surface water due to urban and fertilizer runoff can cause algae blooms that ultimately end up suffocating aquatic organisms in addition to causing a stinky unpleasant smell and increasing water treatment coast (Else-Quirk et al., 2019). On the other hand, warming water holds less dissolved oxygen that fish and other aquatic lives depend on and because of its low dissolved oxygen, the ability of the water body to effectively self-purify through biodegradation is hindered making it unfit for human consumptions (Jarvie et al., 2020; Bougouffa et al., 2013).

A few examples of recent studies that provide compelling evidence on the impact of climate and land use change on water quality around the globe include (Santy et al, 2020; Namugize et al., 2018; Ndulue & Mbajiorgu, 2018). However, there exist divergent views on whether climate or land use change has stronger signature on controlling stream flow, sediment and nutrients loading. Some scholars have reported that the effects of LULCC on hydrological processes are more pronounced than the effects of climate change at the local scale (Khoi et al., 2019; Gallo et al., 2015). This is because land use change starts as a local issue and the effect cascades outwards while climate change is a global issue whose effects are felt globally, regionally, and locally. Additionally, some findings suggest that the effects of LULCC are often contradictory and inconsistent due to the interaction between LULCC and climate change (Luo et al., 2020; Beck et al., 2013). Furthermore, Shrestha et al. (2017); Zhang et al. (2016); Khoi & Suetsugi. (2014),

reported that the combination of LULCC and climate change does not necessarily result in accelerating changes in water quality since the effects of both drivers may also offset each other. On the other hand, Giri et al., (2019); Ndulue and Mbajorgu, (2018); Trang et al. (2017), reported that the interaction between climate change and LULCC may lead to aggravated impacts on water quality. Molina-Navarro et al. (2018) argued that, the consequences of the interactions of climate and land use changes on water quality are uncertain. Thus, studies on future water quality should account for the possible interactions between the impacts of climate and land use changes (Khoi et al., 2019; Serpa et al., 2017).

Mountain ecosystems are at greater risks compared to other landscape. According to the World Bank (2008), the impact of climate change will be more pronounced in high-elevation mountain ranges, which are warming faster than adjacent lowlands. The pace of climate zone shifts will also be higher in such regions than in lowlands (Kohler & Maselli, 2009). In fact, many mountain regions of the world have become increasingly prone to destructive natural processes including earthquakes, volcanic eruptions, dam bursts, glacial lake outbursts, as well as landslides (Kohler & Maselli, 2009). In Mt. Elgon region for example, floods and series of shallow and deep landslides during heavy and sustained rainfall events Mugagga et al. (2012), have claimed many lives and destroyed properties worth millions of dollar in the last three decades (Olago, 2015; World Bank, 2008). The situation is further worsened by the considerable loss of woodlands and forest cover due to deforestation and cultivation, particularly on steep concave slopes of Mt. Elgon (Mugagga et al., 2012). The risk of landslide, flood, soil erosion, and water quality degradation in Mt. Elgon region is expected to rise in future, given the growing population, and the related expansion of settlements, and infrastructure on the mountain (Olago, 2015; World Bank, 2008) hence, a need for more research on the related topics in the area.

A compendium of studies in Mt. Elgon region seems to point towards increasing warming and rainfall of varying trends and magnitudes. For example, Kansiime et al. (2013), found statistically significant increase ($p \leq 0.05$) in annual and seasonal rainfall in the Mt. Elgon region with very high coefficient of variation for August, September, October and, November (ASON) ($CV > 30\%$). In the same study, farmers also perceived increased annual and seasonal rainfall in the region. A similar study in Mbale region by UNDP (2013), reported an increase of between 0.4 and 1.2 °C in monthly temperatures during the 2001-2011 period compared to the 1961-1990

period in line with GCM projected increase in temperature for the period 2011-2040. In Mpologoma catchment in eastern Uganda, Mubialiwo et al. (2020), reported statistically significant increase ($p < 0.05$) in annual and March-May rainfall. Furthermore, authors also found negative statistically significant ($p > 0.05$) October-December, and ($p < 0.05$) June-September rainfall respectively. The study also detected positive sub trends in rainfall in the 1950s and from the mid-2000s till 2016 while negative sub-trends were recorded between 1960 till around 2005.

Water resources management in Uganda faces several problems, such as changes in rainfall patterns, prolonged droughts, increasing frequency of floods, deterioration in water quality and quantity, and degradation of watersheds (MWE, 2019). According to (MWE, 2019), the drivers of reduced river flows are encroachment on water catchments, increased water abstractions for domestic, industrial, infrastructure development, and production. Sironko catchment on the slope of Mt. Elgon in Eastern Uganda is not an exception to the problems faced by other catchments in the country. More so, the government has planned a water-supply investment project in the catchment. However, the proposed project is bound to reduce the flows in the target rivers, denying the ecosystems and social requirements downstream the opportunity for the associated values. Sironko catchment is also known for the spectacular Sipi falls and the unique culturally blended recreational activities from the local communities. These activities attract between 10 and 20 % of all tourists visiting Uganda every year (Fodor & Messerli, 2013). The government collects revenue from these tourists and some of the revenue is used to support local communities' livelihoods. The catchment also lies within one of the most agriculturally productive rural regions of Uganda (UBOS, 2016). Agriculture employs 69 % of the close to 40 million Ugandans and contributes about 23 % to annual Gross Domestic Product (GDP) (FAO, 2018). Despite its importance, the sector is predominantly rain-fed and gets challenged by the variability and change in climate (MWE, 2019). Understanding the variabilities climate is vital for the planning and management of subsistence cropping systems and for the sustainability of water resources and livelihoods in Uganda.

Sironko catchment lies within a fragile environment which is prone to climate related disasters such as droughts, floods, and landslides (UNDP, 2013; Knapen et al, 2006). The region is also one of the most densely populated, rapidly urbanizing rural parts of Uganda (Nakileza et al.,

2017; UBOS, 2016). Population pressure is driving rapid land use changes in the region and all the available lands are intensively cultivated including the steep slopes and river banks (Mugagga et al., 2015; Mugagga et al., 2012). As a result, there is serious problem of sedimentation and river siltation downstream in most of the rivers of Mt. Elgon (Turyahabwe et al, 2020; Stanley et al., 2019) and could be impacting negatively on stream discharge and water quality with serious consequences on the ecosystems and livelihoods downstream. Yet, the catchment is one of the top suppliers of water to Lake Kyoga and River Nile in Uganda. Most of the rivers, streams, and swamps in the Mt. Elgon are recharged and sustained by rainfall (Olago, 2015; World Bank, 2008). Additionally, surface water sources are the most common fresh water suppliers to the communities. However, future provision of clean water in the region is projected to get worse amidst increasing demand and the amount of clean fresh water is expected to reduce as a result of contamination from unprotected water catchments and poor sanitation, in a situation of increased rainfall intensity (World Bank, 2008). In low-lying parts of the ecosystem, fresh water availability is feared to be compromised by increased temperatures and higher rates of evaporation during the long dry spells, causing drying up of water sources such as wells and springs and general scarcity of water (World Bank, 2008). The situation could even be exacerbated by the interactions between future climate and land use change.

Given its importance, the water resources in Mt. Elgon deserve to be guarded against possible future impacts of climate and land use changes. In spite of the above, quantitative data on the impacts of climate and land use changes on water quality in Sironko catchment are still inadequate. Quantitative studies are crucial to manage the expected increased risk of water quality degradation in Mt. Elgon region, given the growing population, and the related expansion of settlements, and infrastructure on the mountain (Olago, 2015; World Bank, 2008). Understanding land use and land cover patterns as well as associated impacts of climate and land use changes on freshwater resources at catchment level is paramount as it can facilitate a dialogue between resources actors to reach consensus (Noordwijk et al., 2020). This study assessed the impacts of climate and land use change on the magnitudes of selected water quality parameters in Sironko catchment. The overall goal was to contribute to improved understanding of the impacts of climate and land use change on water quality.

7.3 Materials and methods

7.3.1 Study area

This objective was accomplished in two parts. The first part involved field assessment of selected water quality parameters in Sironko catchment. Due to resources constrain (time and finances) only a few selected water quality parameters were monitored and the sites were restricted to only 265 km² micro-catchment of river Sironko within an altitude ranged of 1110 to 4304 meters above sea-level (Figure 6.1). For detailed description of Sironko catchment, refer to chapter 3, section 3.1.1-3.1.5.

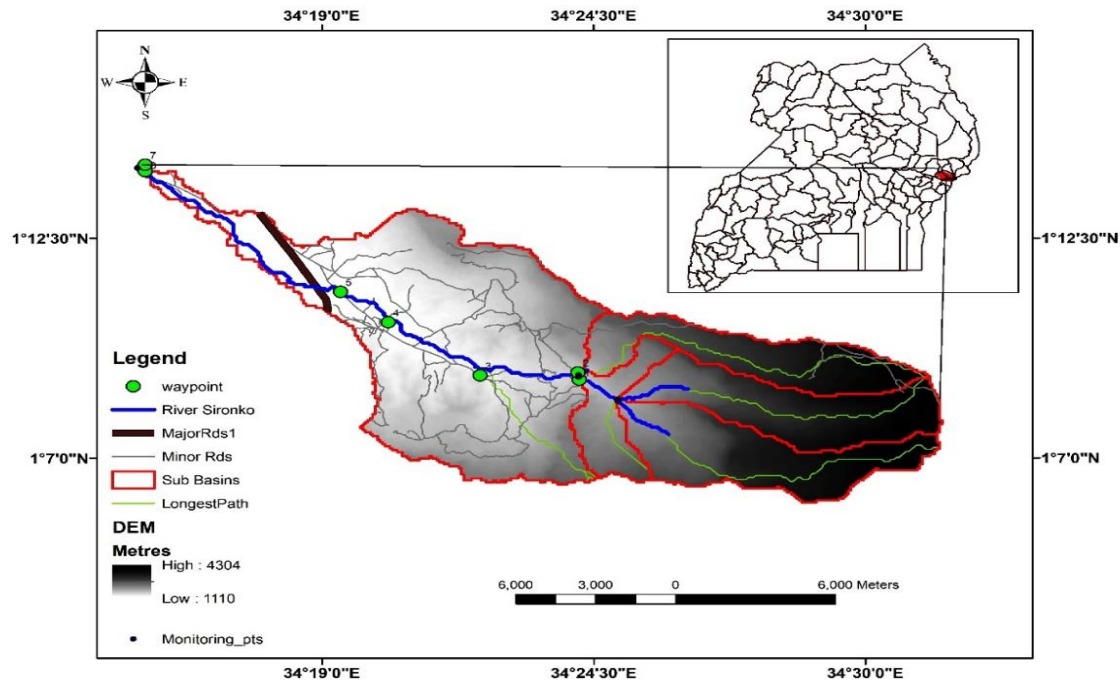


Figure 7.1: The sampling sites locations (way point = sampling site)

7.3.2 Sampling/monitoring sites selection

Seven sampling sites (what were referred to as way points in the legend) were purposively selected along a segment of river Sironko based on the land use and land cover and socio-economic activities. Site 1 is on river Sironko while site 2 is on river Buginyanya which is a tributary of river Sironko. Both site 1 and 2 are located below a conservation area at the end of a forest. The two sites were selected to represent less human disturbance (less impacted sections)

on both the main river and its tributary. These sites were to provide background information on water quality for all the parameters investigated. Site 3 represented a mixture of low agriculture and settlement. It is in a section of the river where local brewing using molasses takes place. Site 4 and site 5 represent the effects of moderate settlement and cultivation on water quality. Both site 6 and 7 are within the Sironko town. The sites represent a lengthy segment of the river under intense agriculture. The farmers in this section of the river heavily rely on chemical fertilizers to support crops such as tomatoes, onions, cabbages. Sand mining as an economic activity is also commonly practiced along the river. Site 7 is located about 1.5 kilometers below site 6 which was meant to represent the total pollution of all the sites.

7.3.3 Samples collection and laboratory analysis

This study considered water quality parameters that affect drinking water standards as per the Uganda National Bureau of Standards (UNBS) guideline for drinking water (UNBS, 2014). It was important to use the UNBS guidelines for drinking water to give the relevancies of the study in the national context. In consideration of time factor and financial resource the capacity (reagents and equipment) at the National Water and Sewerage Corporation (NWSC) laboratory in Mbale was also consider hence, only pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), biological oxygen demand (BOD₅), chemical oxygen demand (COD), total nitrogen (TN), total alkalinity, total hardness, total phosphorus (TP), turbidity, and fecal coliforms were selected and monitored. Water samples were collected between 8.00hrs to 13.00hrs once a month from January to December 2018. The water samples for laboratory analysis were immediately placed in a lightproof insulated cool box containing ice packs with water to ensure rapid cooling. The samples were transported to the National Water and Sewerage Corporation (NWSC) laboratory in Mbale, for analysis. At the laboratory, samples were refrigerated at temperature of 4 °C prior to analysis.

The collected water samples were subjected to the standard procedures for testing physico-chemical and biological water quality for drinking purposes in the field and in the laboratory according (APHA, 2015). Chemical oxygen demand was determined by refluxing a sample in a strongly acid solution with a known excess of K₂Cr₂O₇. Biological oxygen demand was measured by filling an airtight 50 ml sample bottle to overflowing and incubating at 20⁰C for

five days. Dissolved oxygen was measured before and after incubation and BOD is a difference between the initial and final DO. pH was measured using the combined glass-calomel electrodes method. Color, TSS, and $\text{NH}_3\text{-N}$ were determined using a DR/3900 Spectrophotometer. Turbidity was determined by the nephelometric method using a turbid-meter by comparing the amount of light scattered by a standard reference suspension under the same conditions. The more the light dispersed, the higher is the turbidity. Total suspended solids got determined by the gravimetric method. Here, a well-mixed sample was evaporated in a weighed dish and dried to constant weight in an oven at 105°C . The weight differences before and after drying gave the TSS. Total alkalinity was measured based on a neutralization reaction of 0.02 Hydrochloric acid. Total hardness was detected by complexometric titration of the sample using Ethylene diamine tetra-acetic acid (EDTA) in the presence of Eriochrome Black T indicator. Total Iron was measured by the Ferro Zine Iron Reagent method with buffered samples to a pH of 3.5. DO was measured by the Winkler titrimetric method. This method involves the oxidizing property of the dissolved oxygen. While fecal coliforms were quantified using the total plate counts method.

7.4 Climate change scenarios

The climate scenarios used in this study were developed based on annual means of baseline rainfall, temperature (minimum, maximum, mean) for three virtual stations Buginyanya, Kumi, and Nakapiripirit used to downscale and project future climate in Sironko catchment as described in chapter six under section 6.2.3.

7.5 Historical and projected land use land cover change

The historical and projected land use and land cover maps 2000 and 2040 respectively, developed under the specific objective one (chapter four) were used to assess the impacts of land use change on (streamflow, sediment/TSS, TN, and TP). The land use maps were produced following the procedures as described in chapter five section 5.2.3-5.4.4.

7.6 The SWAT model

The SWAT model is a process-based hydrology and water quality model, designed to estimate impacts of land management practices on water quantity and quality in complex watersheds (Srinivasan & Arnold, 2010). The model is a semi-distributed physically-based and computationally efficient model developed for long-term continuous simulations. There are eight

major components of the model: agricultural management, crop growth, hydrology, nutrients, pesticides, sedimentation, soil temperature, and weather. SWAT has been successfully used to investigate the impacts of climate and land use changes on stream discharge and water quality in different catchments around the world: (Ba et al., 2018; Guo et al., 2016; Shao et al., 2018; Liu et al., 2017; Zhang et al., 2016; Gabiri et al., 2020; Zhou & Zhang, 2020).

7.6.1 SWAT model input data

The details of the data required to set up SWAT model is shown in (Table 7.1). The 30 m resolution digital elevation model (DEM) from Shuttle Radar Topography Mission, downloaded from USGS (<http://gdex.cr.usgs.gov/gdex/>) was used for topographic information. Soil data was obtained from the harmonized soil database from the Land and Water Resources, of the United Nations (UN) Food and Agricultural Organization (FAO) soil and Terrain database for eastern Africa at a scale of 5 meters by 5 meters (FAO, 2009). The soil properties of interest in SWAT are soil hydrologic group, maximum rooting depth of soil profile, soil texture, soil layer depth, moist bulk density, available water capacity of soil type, saturated hydraulic conductivity, organic carbon content, moist soil albedo and soil erodability factor. Daily flow data for River Sironko and its tributary Sipi River were obtained from Ministry of Water and Environment. The data record starts from the 1950s' to 2016 but with major gaps. On inspection, the Sironko flow data was discarded because of the huge gaps problem. The daily flow data for Sipi for the period 1998-2010 was qualified and used for calibrating and validating the model. Although, satellite-based data are known to have errors due to their low resolutions, the data have proven very useful especially in places where observational datasets are limited. In Uganda, Egeru et al. (2019); Majaliwa et al. (2015) have successfully used the Modern Era-Retrospective Analysis for Research and Applications (MERRA) data provided by the Agricultural Model Inter-comparison and Improvement Project (AgMIP) for climate change analysis. Last but not least, the land use maps of Sironko catchment in 1986, 2000, 2016, and 2040 were produced following the steps described in chapter four of this thesis.

Table 7.1: Model input data

Input data	Station/Location	Source	Resolution
Rainfall	Buginyanya, Kumi and Nakapiripirit	MERRA	Daily (mm)
Temperature	Buginyanya, Kumi and Nakapiripirit	MERRA	Daily ($^{\circ}\text{C}$)
Streamflow	Sipi river gauge	MWE	Daily (m^3/s)
DEM	Uganda	USGS	(30*30) m
Soil Data	Africa	FAO	(5*5) m
Land use land cover	Sironko catchment	USGS	(30*30) m

7.6.2 Model set up

The Sironko catchment was delineated using ArcSWAT incorporated in ArcGIS interface. The process involved DEM setup, stream definition, catchment outlet selection and hydrological response unit (HRU) definition and calculation of sub-basin parameters. The catchment was delineated into sub-basins and Hydrological Response Units (HRUs). HRUs consist of homogenous land use, management, topographical, and soil characteristics. The HRUs were created using the Arc-SWAT-HRUs analysis tool through setting the threshold of land use over sub-basins to 5 %, soil class over land use area to 5 %, and slope class over soil area at 10 %. SWAT model was then run on a daily time scale from 1998 to 2010 including 2 years' warmup period.

7.6.3 Sensitivity analysis

The first step towards calibration and validation of SWAT model is sensitivity analysis. Sensitivity analysis was performed using the global sensitivity approach in semi-automated Sequential Uncertainty Fitting (SUFI-2) algorithm in SWAT-Calibration Uncertainty Programs (SWAT-CUP) package version 5.2.1.1 (Abbaspour et al., 2017). The flow parameters for

Sironko catchment used for sensitivity analysis are in (Appendix 9) and the sensitivity rankings are shown in (Appendix 10).

7.6.4 Model calibration and validation

The calibration and validation of the model was conducted using the Sequential Uncertainty Fitting (SUFI-2) algorithm in SWAT-Calibration Uncertainty Programs (SWAT-CUP) package version 5.2.1.1 (Abbaspour et al., 2017). Although river flow data was available starting from the 1960s to 2010,' the data had gaps that could not be filled using known scientific methods. As such, river flow data for 1998-1999 was used as warm-up before the model was calibrated from 2000 to 2006 and validated from 2007 to 2010 on a daily time scale. Furthermore, monitored water quality dataset periods (January 2018-December 2018) was not long enough to be used for calibration and validation. SWAT also has an inbuilt algorithm which automatically generates sediments and nutrients values in the process of calibration and validation using given flow data. Consequently, the model was calibrated and validated for river flow only. In data limited environment, SWAT has been highly recommended to simulate the impacts of climate and land use land cover changes on water quality (Akoko et al., 2021).

7.6.5 SWAT model performance evaluation

The performance of the model was assessed using graphical comparison between observed and simulated values and using statistical indices the Coefficient of Determination (R^2) Equation 7.1, the Nash Sutcliffe Efficiency Coefficient (NSE) Equation 7.2, and the percent Bias (PBIAS) Equation 7.3, respectively. Model performance evaluation confirms the relationship between the observed and simulated values and test the robustness of the model.

$$R^2 = \frac{\left[\sum_{i=1}^n (O_i - \bar{O})(S_i - \bar{S}) \right]^2}{\sum_{i=1}^n (O_i - \bar{O})^2 \times \sum_{i=1}^n (S_i - \bar{S})^2} \quad (7.1)$$

where O_i is the observed daily discharge, S_i is the simulated daily discharge, $\bar{O}$ is the average measured discharge, $\bar{S}$ is the average simulated discharge and n is the total number of observations.

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (7.2)$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - S_i) \times 100}{\sum_{i=1}^n (O_i)} \quad (7.3)$$

7.6.6 Impact of climate and land use change on the magnitudes of selected water quality parameters in Sironko catchment between 2025 and 2040

The near future (2025-2040) streamflow, sediment/TSS, and nutrients loads were estimated using the SWAT model which was calibrated and validated for flow only due to data limitations. Four runs/pseudo experiments were implemented to separate the individual and combined impacts of climate and land use changes. Run one (baseline condition) was performed using the historical climate from 1980 to 2009 and historical land use of 2000 under both RCP 4.5 and RCP 8.5, respectively. Run two was performed using the projected climate from 2025 to 2040 and historical land use of 2000 to estimate the impact of climate change alone. The simulated flow, sediment, and TN, TP loads under RCP 4.5 and RCP 8.5 scenarios between 2025 and 2040 were then compared with baseline flow, sediment, TN, and TP loads from 1980 to 2009, respectively. Similarly, to estimate the impact of land use change alone, the third run was implemented using projected land use in 2040 and historical climate from 1980 to 2009 under both RCP 4.5 and RCP 8.5. The impact of land use change was then derived by comparing the simulated flow, sediment, TN, and TP loads between 2025 and 2040 under RCP 4.5 and RCP 8.5 with baseline flow, TN, TP, and sediment loads from 1980 to 2009, respectively. To obtain the combined impacts of climate and land use changes, the model was run using the projected climate and projected land use. The simulated flow, sediment, TN, and TP under RCP 4.5 and RCP 8.5 scenarios were then compared with baseline flow, sediment, TN, and TP loads respectively.

7.7 Data analysis

Measured water quality datasets were subjected to descriptive statistics (mean and standard deviation) for each of the seven monitoring sites using Microsoft excel 2016 package. The obtained mean values of monitored parameters were compared with the Uganda National Bureau of Standards (UNBS) guideline for natural portable water UNBS (2014), based on two clusters: 1) wet season combining the first rainfall season March, April, and May (MAM); and the second rainfall season September, October, and November (SON). 2) dry season comprising the months of December, January, and February (DJF); and June, July, and August (JJA) respectively. t-test was carried out at a significant level of 0.05 in IBM SPSS 20 to determine any significant difference in water quality parameters during dry and wet seasons and baseline and future scenarios.

SWAT model output data was analyzed using one-way sample t-test to confirm if the historical (1980-2009) and near future scenarios (2025-2040) stream flow, sediment/TSS, TN, and TP loads in Sironko catchment are not significantly different. The contribution of land use and land cover and climate on stream flow, sediment/TSS, TN, and TP loads, were computed using a regression model performed on a second powered matrix model output from climate (historical, future) and land use and land cover (historical, future) variables to confirm if climate and LULCC are likely to equally impact stream flow, sediment/TSS, TN, and TP in the near future scenarios (2025-2040). The statistical analyses took place in Microsoft excel and IBS Statistical Package for Social Scientists (SPSS) version 20.

7.8 Results

7.8.1 Variability of selected water quality parameters in dry and wet season

The variability in monitored water quality parameters by sampling site and seasons were compared against the Uganda National Bureau of Standards (UNBS) guideline for natural portable water as presented in Table 7.2 and 7.3, respectively.

The result in Table 7.2 indicates that in dry season, the mean values for most of the parameters for the different sites fall within the UNBS critical values except for turbidity whose mean values were above the UNBS critical values for all the sites except site 1 and 2, and fecal coliforms at site 7.

Table 7.2: The mean values of selected water quality parameters by monitoring site along a segment of river Sironko in dry season against national standards.

Parameters	Site 1 (n=12)	Site 2 (n=12)	Site 3 (n=12)	Site 4 (n=12)	Site 5 (n=12)	Site 6 (n=12)	Site 7 (n=12)	UNBS
TSS (mg/L)	17.25	10.33	42.33	34.17	17.33	21.83	46.17	100.00
Turbidity (NTU)	19.91	13.84	33.82	36.04	23.59	67.71	66.50	25.00
TDS (mg/L)	46.28	34.47	64.50	69.18	72.60	86.57	85.80	1500.00
pH	8.32	8.35	8.03	7.98	8.10	8.11	8.05	5.5-9.5
E. C ($\mu\text{Sm}/\text{cm}$)	98.73	70.65	140.42	151.17	166.33	198.17	192.67	2500.00
Nitrogen (mg/L)	1.13	0.50	1.94	2.05	1.99	2.40	3.49	45.00
Phosphorus (mg/L)	0.04	0.02	0.21	0.17	0.17	0.19	0.22	2.20
Alkalinity (mg/L)	71.33	54.00	76.00	84.00	79.33	92.67	126.33	800.00
Hardness (mg/L)	76.33	61.33	84.33	90.00	87.67	109.33	114.67	500.00
BOD5 (mg/L)	4.19	2.97	5.79	6.48	5.05	7.91	9.94	50.00
COD (mg/L)	6.39	5.34	9.06	8.01	7.84	13.00	16.47	100.00
DO (mg/L)	6.81	6.86	6.79	6.82	6.74	6.65	6.62	>2
Fecal coliforms (numbers/mL)	15.00	16.50	26.17	54.33	41.33	25.00	68.00	50.00

Where n = number of samples per site

Similarly, Table 7.3 indicates that in wet season the mean value for TSS at site 7, turbidity site 2-7, and Fecal coliform at site 1-7 were above the UNBS critical standard.

Table 7.3: The mean values of selected water quality parameters by monitoring site along a segment of river Sironko in wet season against national standards

Parameters	Site 1 (n=12)	Site 2 (n=12)	Site 3 (n=12)	Site 4 (n=12)	Site 5 (n=12)	Site 6 (n=12)	Site 7 (n=12)	UNBS
TSS (mg/L)	12.50	29.17	25.33	49.17	53.83	65.83	101.33	100.00
Turbidity (NTU)	9.77	37.57	37.99	59.74	80.09	95.26	128.50	25.00
TDS (mg/L)	42.62	37.73	51.73	51.42	54.80	64.28	68.85	1500.00
pH	7.83	7.82	7.85	7.85	7.85	7.72	7.76	5.5-9.5
E. C ($\mu\text{Sm/cm}$)	89.73	81.82	112.83	105.23	139.48	190.30	192.65	2500.00
Nitrogen (mg/L)	1.10	0.48	1.44	1.37	1.80	2.21	2.57	45.00
Phosphorus (mg/L)	0.08	0.05	0.23	0.15	0.17	0.18	0.24	2.20
Alkalinity (mg/L)	83.67	66.33	82.33	80.00	101.33	127.67	156.33	800.00
Hardness (mg/L)	89.33	83.67	96.00	106.67	127.33	131.67	139.67	500.00
BOD5 (mg/L)	5.02	5.19	9.51	11.14	6.07	9.34	12.09	50.00
COD (mg/L)	10.62	9.84	15.25	14.52	12.82	15.47	19.57	100.00
DO (mg/L)	6.85	6.88	6.83	6.75	6.74	6.68	6.67	>2
Fecal coliforms (count/mL)	52.50	54.50	68.83	101.50	219.50	249.83	322.33	50.00

Where n = number of samples per site

7.8.2 Differences in mean values of selected water quality parameter between wet and dry seasons

The Null hypotheses of no significant seasonal difference on the magnitudes of selected water quality parameters in Sironko catchment was tested using t-test (Table 7.4). The results indicate significant difference ($p < 0.05$) in pH, EC, TP, and DO between dry and wet season.

Table 7.4: Differences in water quality between wet and dry seasons

Pair	Parameters-Season	Mean	STDVE	t-test	p-value
1	TSS (mg/L)-Dry season	27.06	13.83	3.56	0.17
	TSS (mg/L)-Wet season	48.17	29.79		
2	Turbidity (NTU)-Dry season	37.34	21.72	3.79	0.16
	Turbidity (NTU)-Wet season	64.13	40.27		
3	TDS (mg/L)-Dry season	65.63	19.38	9.44	0.07
	TDS (mg/L)-Wet season	53.06	11.01		
4	pH-Dry season	8.13	0.14	49.81	0.01
	pH-WET season	7.81	0.05		
5	E. C ($\mu\text{Sm/cm}$)-Dry season	145.45	47.05	18.19	0.03
	E. C ($\mu\text{Sm/cm}$)-Wet season	130.29	45.65		
6	Nitrogen (mg/L)-Dry season	1.93	0.94	9.72	0.07
	Nitrogen (mg/L)-Wet season	1.57	0.70		
7	Phosphorus (mg/L)-Dry season	0.15	0.08	0.31	0.02
	Phosphorus (mg/L)-Wet season	0.16	0.07		
8	Alkalinity (mg/L)-Dry season	83.38	22.40	11.24	0.06
	Alkalinity (mg/L)-Wet season	99.67	31.76		
9	Hardness (mg/L)-Dry season	89.09	18.36	9.28	0.07
	Hardness (mg/L)-Wet season	110.62	22.27		
10	BOD5 (mg/L)-Dry season	6.05	2.34	6.28	0.10
	BOD5 (mg/L)-Wet season	8.34	2.90		
11	COD (mg/L)-Dry season	9.44	3.94	5.13	0.12
	COD (mg/L)-Wet season	14.01	3.29		
12	DO (mg/L)-Dry season	6.76	0.09	1.35	0.00
	DO (mg/L)-Wet season	6.77	0.08		
13	Fecal coliforms (count/mL)-Dry season	35.19	20.09	1.60	0.36
	Fecal coliforms (count/mL)-Wet season	152.71	109.55		

Note: STDVE = Standard deviation

7.8.3 Model calibration and validation

Results show that stream flow was significantly sensitive ($P < 0.05$) to (SOL_AWC, CH_N2, SOL_K, and ESCO) in (Appendix 12). From Figure 7.2, it is seen that during calibration, SWAT failed to pick some of the daily peak flows. However, during validation, the model picked the daily peak flows Figure 7.3 much more accurately since validation used only the most sensitive flow parameters.

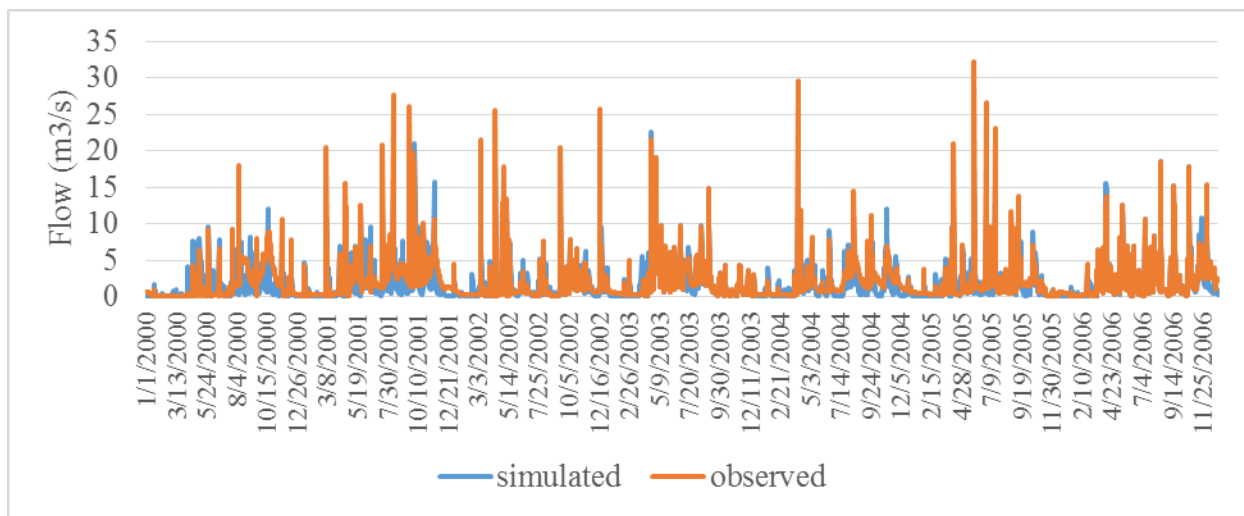


Figure 7.2: Daily discharge calibration in Sironko catchment (2000-2006)

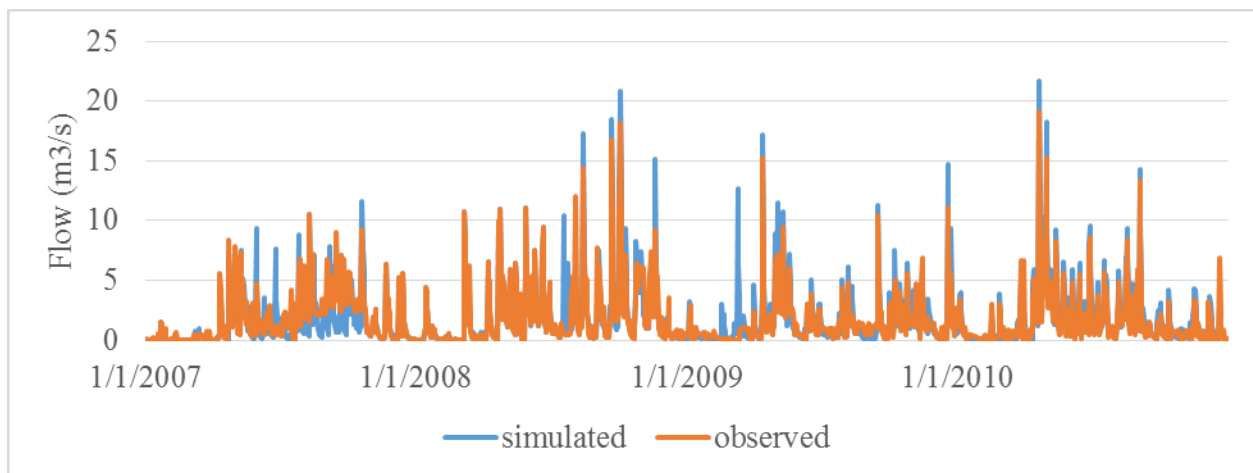


Figure 7.3: Daily discharge during validation in Sironko catchment 2007-2010

7.8.4 Model performance evaluation

Daily flow statistics in Table 7.5 suggests a strong correlation between the simulated and observed stream flow for both calibration (1998-2006) and validation (2007-2010). The Nash Sutcliffe Coefficients for the calibration and validation were 0.71 each while the coefficient of determinations R^2 , Table 7.5 and Figure 7.4 were 0.72 for calibration and Figure 7.5 0.77 for validation, respectively. The overall performance of the model suggests that although the model failed to accurately pick peak flows during calibration, it successfully captured the important parameters of flow (Appendix 12) and could therefore be used to evaluate the impacts of climate and land use simulate stream flow, sediment, and nutrients loading in Sironko catchment.

Table 7.5: Summery statistics for SWAT performance evaluation

Model stage	Evaluation statistics					
	R^2	NSE	RSR	PABIS (%)	p-value	r-factor
Calibration (2000-2006)	0.72	0.71	0.53	5.1	0.26	0.05
Validation (2007-2010)	0.77	0.71	0.54	-4.8	0.3	0.06

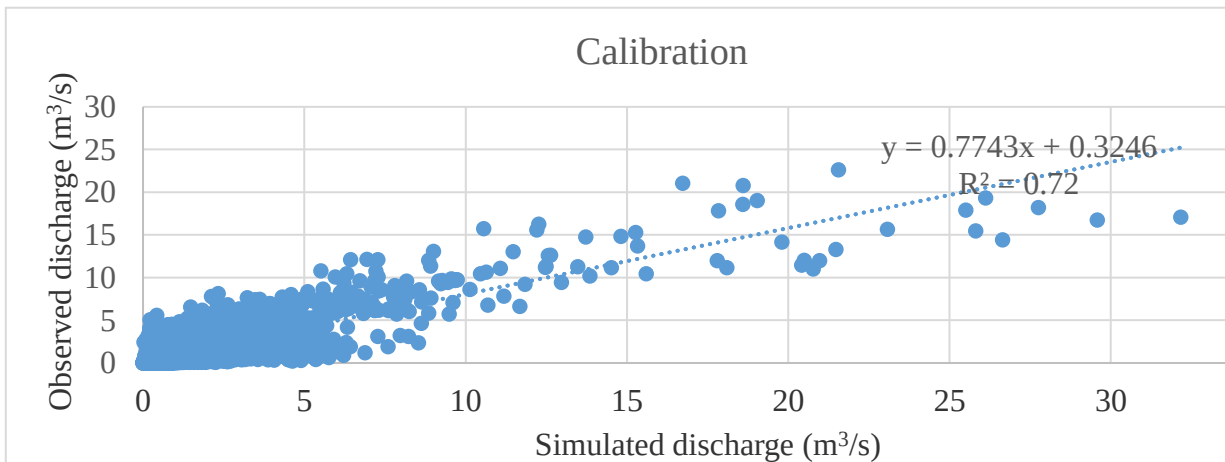


Figure 7.4: Scatter plot of observed and simulated discharge for calibration period (2000-2006)

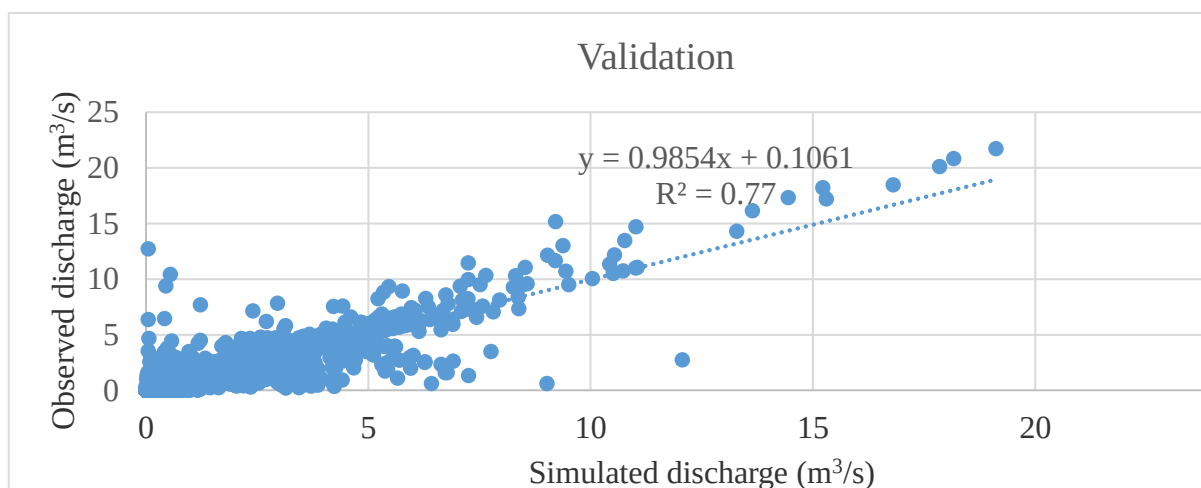


Figure 7.5: Scatter plot of observed and simulated discharge for Validation period (2007-2010)

7.8.5 Flow, sediment and nutrient transported in Sironko catchments from 1980 to 2009

Once SWAT model was calibrated and validated for stream flow, the model automatically generated sediments and nutrients values based on the different land use land cover types of Sironko catchment. Therefore, the sediment yield/load and nutrients load in Sironko catchment from 1980 to 2009 is presented in (Table 7.6). Accordingly, the result indicates between 1980 and 2009, the mean flow was 4.69 m³/s with a very high variability in stream flow, sediment loads and TP with CV = 77.40 %; 53.6 %; and 43.2 % respectively. It was however, not possible to correlate the model predictions with actual measurements because the measurements were for only one year and for only a section of Sironko catchment while model predictions summed up the parameters over the entire catchment at the outlet,

Table 7.6 Annual average flow, sediment and nutrient loads in Sironko catchment from 1980 to 2009

Flow (m ³ /s)	Flow (m ³ /s)	Sediment load (tons/year)	TN (kg/day)	TP (kg/day)	Sediment yield (tons/km ² /year)
Mean	4.69	944.45	3172.55	1.69	0.24
STDVE	3.63	506.92	673.19	0.73	0.18
CV (%)	77.40	53.67	21.22	43.20	75.00

Note: STDVE = Standard deviation and CV = Coefficient of variations

7.8.6 Projected changes in stream flow, TSS, TN, and TP loads for 2025-2040 compared to 1980-2009

Stream flow variation in Sironko catchment is presented in (Figure 7.6). The figure shows that under Cool-wet climate grime, climate change will lead to variation in stream flow in the near future 2025-2040 in the range of 17.04 % to 29.12 % and under RCP 4.5 and RCP 8.5 respectively. On the other hand, stream flow will vary under the influence of land use change alone in the range of 3.81 % to 9.74 % under RCP 4.5 and RCP 8.5 respectively. The combined impacts of climate and land use change however, will cause changes in flow in the range of 62.23 % to 74.30 % under RCP 4.5 and RCP 8.5 respectively. Under Cool-dry condition, climate change effect on stream flow in the near future 2025-2040 will vary between -4.05 % to -20.47 % under RCP 4.5 and RCP 8.5 respectively. On the other hand, stream flow will vary under the influence of land use change alone in the range of -4.90 % to 15.14 % under RCP 4.5 and RCP 8.5 respectively. The aggregated impacts of climate and land use change will under Cool/dry climate will meanwhile cause a change of 43.07 % to 24.63 % under RCP 4.5 and RCP 8.5 respectively.

Similarly, under Hot-wet climate grime, the effect of climate change alone will alternate stream flow in the near future 2025-2040 by 36.60 % to 40.31 % under RCP 4.5 and RCP 8.5 respectively. But stream flow will vary under the influence of land use change alone in the range of 24.45 % to 29.34 % under RCP 4.5 and RCP 8.5. The combined impacts of climate and land use will produce change in stream flow between 92.76 % to 99.50 % under RCP 4.5 and RCP 8.5 respectively. In the same vine, under Hot-dry climate condition, climate change will lead to alternation in stream flow in the near future 2025-2040 by -20.99 % to -29.11 % under RCP 4.5 and RCP 8.5 respectively. Additionally, the influence of land use change alone will produce a change in stream flow in the range of -14.60 % to -22.33 under RCP 4.5 and RCP 8.5 while the combined impact will generate between 24.91 % to 13.11 % under RCP 4.5 and RCP 8.5 respectively.

Finally, under middle climate grime climate change impact on stream flow in the near future 2025-2040 will be in the range of 7.10 % to 15.06 % under RCP 4.5 and RCP 8.5 whereas land use change alone will result in a change is stream flow in the range of 13.34 % to 15.06 % under

RCP 4.5 and RCP 8.5 respectively. The aggregated effects of the two agents on stream flow meanwhile will be between 66.89 % to 76.20 % under RCP 4.5 and RCP 8.5 respectively.

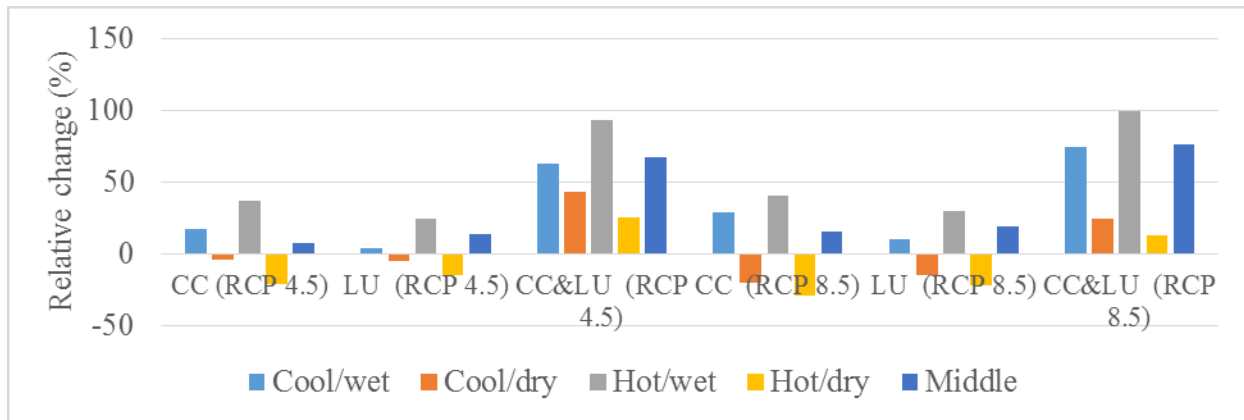


Figure 7.6 Projected stream flow in Sironko catchment in 2025-2040 compared to baseline period 1980-2009

Sediment load variation in the near future 2025-2040 in Sironko catchment is presented in (Figure 7.7). The figure suggests that under Cool-wet condition, sediment load will increase in the range of 29.19 % to 36.55 % under the influence of climate change alone under RCP 4.5 and RCP 8.5 respectively. On the other hand, land use change will increase sediment loading by between 32.47 % to 39.34 % under RCP 4.5 and RCP 8.5. Moreover, the combined impacts of climate and land use change will escalate sediment load by between 97.06 % to 106.23 % under RCP 4.5 and RCP 8.5. Likewise, assuming Cool-dry condition in Sironko catchment between 2025 and 2040, climate change alone will lead to increase and decrease sedimentation by 15.67 % and -11.33 % respectively under RCP 4.5 and RCP 8.5 scenarios. On the other hand, land use change will drive sediment loading in the range of 17.36 % to 11.59 % under RCP 4.5 and RCP 8.5 for a Cool-dry climate in the near future. Otherwise, the aggregated impacts of climate and land use change will increase sediment load by between 75.19 % to 44.47 % under RCP 4.5 and RCP 8.5, respectively.

Given a Hot-wet condition in Sironko catchment between 2025-2040, sediment load will increase by between 12.46 % and 15.16 % under the influence of climate change for RCP 4.5 and RCP 8.5 scenarios respectively. Land use change meanwhile will decrease sediment loading in the catchment by between -19.54 % to -21.21 % under RCP 4.5 and RCP 8.5. Similarly, under

the combined impacts of climate and land use change, sediment load will increase to the tune of 36.69 % to 54.55 % under corresponding RCP 4.5 and RCP 8.5 respectively. However, given Hot-dry condition in the catchment, sediment load will decrease under the influence of climate change by between -2.59 % to -8.04 % under RCP 4.5 and RCP 8.5 respectively. Similarly, land use change will reduce sediment loading in Sironko river in the range of -22.15 % to -31.39 % under RCP 4.5 and RCP 8.5. The two agents however will lead to increased sediment by between 26.56 % to 26.27 % under RCP 4.5 and RCP 8.5.

Lastly, under middle condition, sediment load will decrease under the influence of climate change alone in the range of -14.32 % to -15.69 % under RCP 4.5 and RCP 8.5 respectively. Under the impact of land use change alone, sediment will decrease and increase by -7.51 % and 29.04 % respectively under RCP 4.5 and RCP 8.5. However, the combined impacts of climate and land use change will increase sediment load to the tune of 35.33 % to 48.83 % under RCP 4.5 and RCP 8.5 respectively.

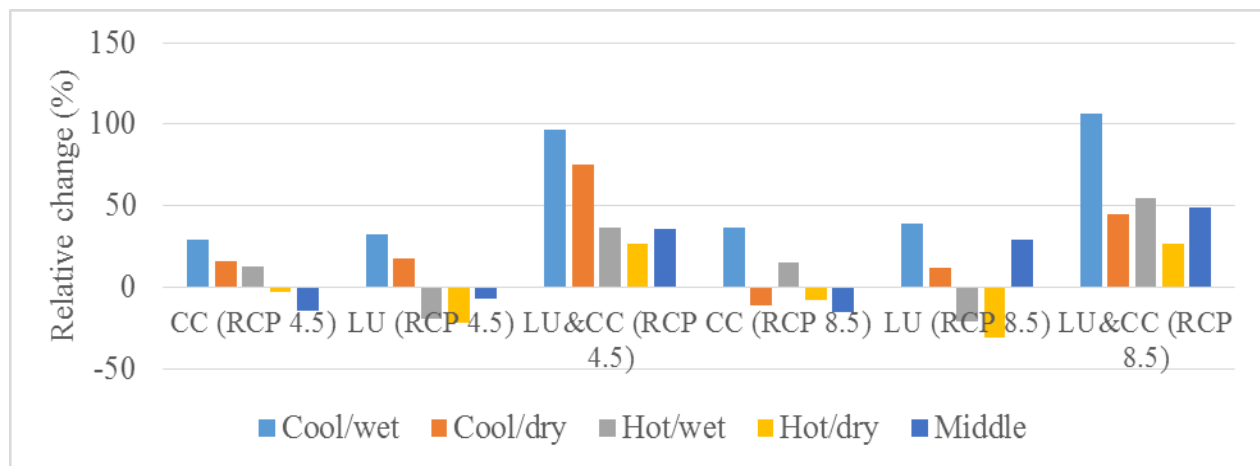


Figure 7.7: Projected sediment loading in Sironko catchment in 2025-2040 compared to baseline period 1980-2009

Projected loading of TN in Sironko catchment in the near future 2025-2040 is presented in Figure 7.8. The result suggests that given a Cool-wet condition in the catchment in 2025-2040, TN load under Cool-wet climate will increase between by 23.17 % to 31.23 % under RCP 4.5 and RCP 8.5 under climate change impact alone. On the other hand, land use change will increase TN load by 27.07 % to 45.52 % under RCP 4.5 and RCP 8.5 respectively while under the combined impacts of climate and land use change, TN will increase in the range of 88.66 %

to 111.14 % under RCP 4.5 and RCP 8.5 scenarios respectively. For Cool-dry condition meanwhile, TN load will reduce under climate influence by -21.35 % to -26.36 % under RCP 4.5 and RCP 8.5 under RCP 4.5 and RCP 8.5 respectively. On the other hand, it will decrease under land use change effect alone by -4.17 % to -16.23 % under RCP 4.5 and RCP 8.5. Otherwise, the combined impacts of climate and land use change in will increase TN in the range of 35.15 % to 20.59 % under RCP 4.5 and RCP 8.5 respectively.

For a Hot-wet climate regime, TN load given Hot-wet climate will increase by 12.89 % to 19.47 % under RCP 4.5 and RCP 8.5 due to climate change impact while land use change will increase TN by 15.65 % and 30.34 % under RCP 4.5 and RCP 8.5 respectively. Additionally, the tow agents will increase TN load in the range of 72.10 % to 90.08 % under RCP 4.5 and RCP 8.5 respectively. In a similar way, under Hot-dry condition it is projected that TN load will decrease between by -20.48 % to -32.65 % under RCP 4.5 and RCP 8.5 under climate change impact alone. But land use change will reduce TN by between -26.93 % to -24.53 % under RCP 4.5 and RCP 8.5 scenarios respectively. Otherwise, TN will increase due to the combined impacts of climate and land use change in the range of 12.83 % to 9.15 % under RCP 4.5 and RCP 8.5 respectively. Whereas under Middle climate condition, TN load will drop by -48.44 % to -40.66 % due to climate change impact alone under RCP 4.5 and RCP 8.5 under and by -32.15 % to -40.66 % due to land use change under RCP 4.5 and RCP 8.5 respectively. However, together, climate and land use change will decrease TN load in the range of -6.37 % to -13.91 % under RCP 4.5 and RCP 8.5 respectively.

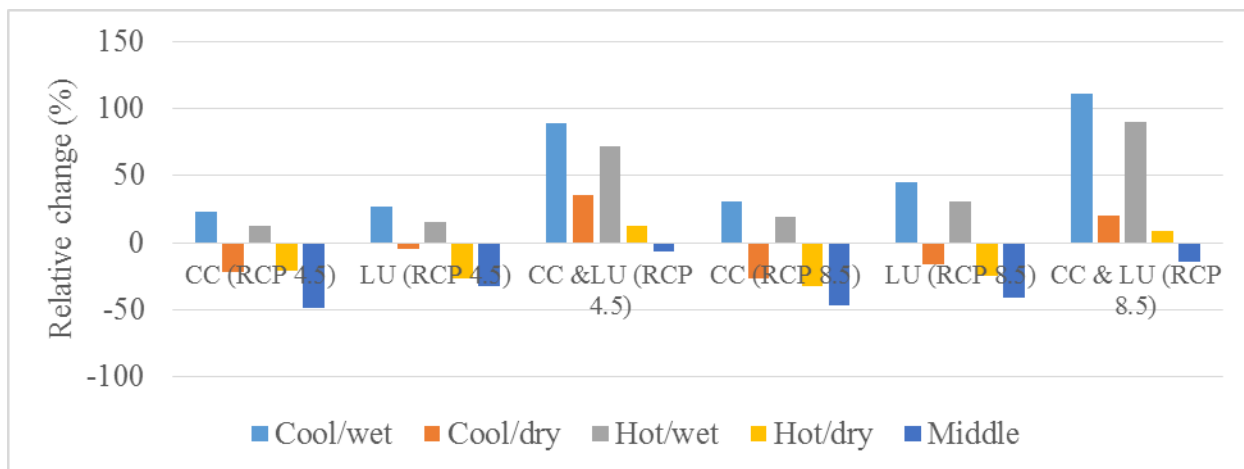


Figure 7.8 Projected annual average TN load in Sironko catchment in 2025-2040 compared to baseline period 1980-2009

The projected variations in TP loading in Sironko catchment from 2025 to 2040 is presented in (Figure 7.9). Results indicate that under Cool-wet condition, climate change will lead to increase in TP load of between 8.67 % to 18.90 % under RCP 4.5 and RCP 8.5 scenarios respectively. Under the impact of land use change alone, TP even increase further to the tune of 9.22 % to 32.13 % under RCP 4.5 and RCP 8.5 respectively. Additionally, the aggregated impact of climate and land use change, it will escalate TP loading in the range of 7.86 % to 91.58 % under RCP 4.5 and RCP 8.5 respectively. On the other hand, for Cool-dry condition, TP will vary between -0.23 to 9.58% under RCP 4.5 and RCP 8.5 respectively due to climate change impact. Additionally, land use change will decrease TP by -14.01% to -40.54% for RCP 4.5 and RCP 8.5 respectively. However, the aggregated impact of climate and land use change, TP will vary in the range of -4.28% to 14.25% under RCP 4.5 and RCP 8.5 respectively.

For a Hot-wet regime, TP will decrease by -28.74 % to -21.82 % under RCP 4.5 and RCP 8.5 due to climate change influence but increase by 37.66 % to 44.67 % for RCP 4.5 and RCP 8.5 respectively under the influence of land use change. Moreover, the aggregated impact of climate and land use change for the Hot dry condition will lead to variation in TP will in the range of -5.86 % to 85.75 % under RCP 4.5 and RCP 8.5 respectively. Meanwhile for Hot-dry condition, climate change will drive a reduction in TP load by -3.47 % to -1629 % under RCP 4.5 and RCP 8.5. Similarly, under the impact of land use change alone, TP will decrease by -33.02 % to -37.60 % for RCP 4.5 and RCP 8.5 respectively. Otherwise, the aggregated impact of climate and

land use change will decrease and increase TP by -11.82 % and 4.21 % respectively under RCP 4.5 and RCP 8.5.

But TP will decrease under Middle climate condition by -27.03 to -19.99 % under RCP 4.5 and RCP 8.5 due to climate change impact but decrease and increase by -7.44 % and 58.27 % respectively under RCP 4.5 and RCP 8.5 scenarios respectively. However, of climate and land use change together will vary TP load in the range of -18.20 % to 98.28 % under RCP 4.5 and RCP 8.5 respectively.

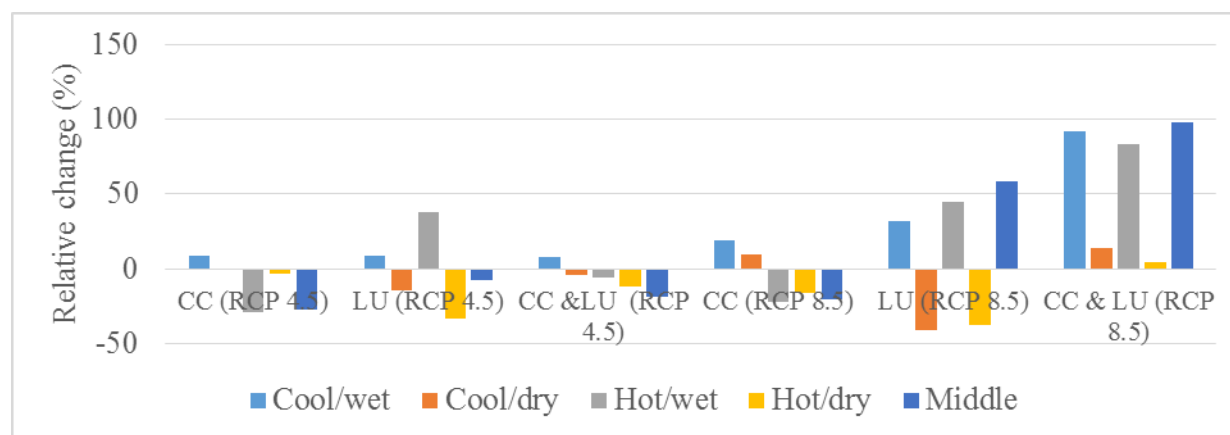


Figure 7.9 Projected annual average TP load in Sironko catchment from 2025 to 2040 compared to baseline period between 1980 and 2009

7.8.7 Contributions of near future (2025-2040) climate and land use land cover changes in 2040 on stream flow, sediment/TSS, TN, and TP in Sironko catchment

The impact of climate and LULCC on selected water quality parameters in Sironko catchment in the baseline and future scenarios under RCP 4.5 and 8.5 were tested using t-test Table 7.7 and 7.8. The result indicates significance difference ($p < 0.05$) between the historical and near future (2025-2040) stream flow, sediment/TSS, TN, and TP loads in Sironko catchment under RCP 4.5.

Table 7.7: t-test of significance difference between historical (1980-2009) and projected (2025-2040) stream flow, TSS, TN and TP in Sironko catchment under RCP 4.5 for Cool/wet; Cool/dry; Hot/wet; Hot/dry; and Middle climate regimes.

Pseudo-experiment	Flow m³/s (p-values)	TSS kg/year (p-values)	TN kg/day (p-values)	TP P kg/day (p-values)	Climate Regimes
Hist (C)- Pro (L)	0.03	0.08	0.07	0.02	Cool-wet
Pro (C)-Hist (L)	0.07	0.09	0.07	0.03	Cool-wet
Pro (L)- Pro (C)	0.05	0.08	0.07	0.02	Cool-wet
Hist (C)- Pro (L)	0.09	0.04	0.08	0.00	Cool-dry
Pro (C)-Hist (L)	0.10	0.05	0.02	0.05	Cool-dry
Pro (L)- Pro (C)	0.10	0.05	0.04	0.03	Cool-dry
Hist (C)- Pro (L)	0.02	0.04	0.04	0.12	Hot-wet
Pro (C)-Hist (L)	0.01	0.28	0.22	0.15	Hot-wet
Pro (L)- Pro (C)	0.00	0.10	0.15	0.05	Hot-wet
Hist (C)- Pro (L)	0.15	0.01	0.07	0.01	Hot-dry
Pro (C)-Hist (L)	0.13	0.08	0.10	0.13	Hot-dry
Pro (L)- Pro (C)	0.15	0.08	0.09	0.07	Hot-dry
Hist (C)- Pro (L)	0.06	0.05	0.20	0.10	Middle
Pro (C)-Hist (L)	0.03	0.03	0.12	0.03	Middle
Pro (L)- Pro (C)	0.03	0.19	0.16	0.06	Middle

Similarly, the result in Table 7.8 indicates that there was significance difference ($p < 0.05$) between the historical and near future (2025-2040) stream flow, sediment/TSS, TN, and TP loads in Sironko catchment under RCP 8.5.

Table 7.8: t-test of significance difference between historical (1980-2009) and projected (2025-2040) flow, TSS, TN and TP in Sironko catchment under RCP 8.5 for Cool/wet; Cool/dry; Hot/wet; Hot/dry; and Middle climate regimes.

Pseudo-experiment	Flow m ³ /s (p-values)	Sediment kg/year (p-values)	TN kg/day (p-values)	TP P kg/day (p-values)	Climate Regimes
Hist (C)- Pro (L)	0.08	0.10	0.08	0.05	Cool-wet
Pro (C)-Hist (L)	0.05	0.10	0.12	0.08	Cool-wet
Pro (L)- Pro (C)	0.02	0.10	0.10	0.12	Cool-wet
Hist (C)- Pro (L)	0.07	0.04	0.10	0.03	Cool-dry
Pro (C)-Hist (L)	0.13	0.03	0.06	0.16	Cool-dry
Pro (L)- Pro (C)	0.14	0.01	0.06	0.06	Cool-dry
Hist (C)- Pro (L)	0.03	0.04	0.06	0.08	Hot-wet
Pro (C)-Hist (L)	0.01	0.08	0.08	0.11	Hot-wet
Pro (L)- Pro (C)	0.01	0.02	0.07	0.03	Hot-wet
Hist (C)- Pro (L)	0.18	0.03	0.12	0.06	Hot-dry
Pro (C)-Hist (L)	0.16	0.12	0.09	0.16	Hot-dry
Pro (L)- Pro (C)	0.17	0.06	0.11	0.10	Hot-dry
Hist (C)- Pro (L)	0.04	0.06	0.19	0.07	Middle
Pro (C)-Hist (L)	0.03	0.08	0.16	0.14	Middle
Pro (L)- Pro (C)	0.03	0.05	0.02	0.02	Middle

The contributions of near future (2025-2040) climate and land use and land cover in 2040 on stream flow, sediment/TSS, TN, and TP under RCP 4.5 and RCP 8.5 for Cool/wet; Cool/dry; Hot/wet; Hot/dry; Middle; and ensemble of climate regimes are presented in Table 7.9 and 7.10 respectively. Both climate and LULCC will have significant impacts on stream flow ($P < 0.05$) under Hot-wet, Hot-dry, Cool-dry and middle regimes. On the other hand, only climate change will have significant impacts on stream flow under Cool-wet and TN under Cool-dry conditions. Likewise, only land use and land cover LULCC will have significant impact on TN under Cool-wet. Table 7.9 also shows that climate is likely to have a higher impact on stream flow than LULCC. On the other hand, LULCC is likely to have a higher impact on TN flux than climate change under RCP 4.5. At this point the hypothesis that only climate change is likely to have a significant effect on stream flow in Sironko catchment in the future scenarios rejected.

Furthermore, the hypothesis that only LULCC is likely to have a significant effect on nitrogen as opposed to climate change in Sironko catchment in the future scenarios is also rejected. Considering TP in Sironko catchment in the future scenarios, LULCC will have a significant impact on TP for a middle climate regime. At this point, the hypothesis that Nitrogen in Sironko catchment will significantly change in future as opposed to phosphorus is rejected.

Table 7.9: Contribution of near future climate (2025-2040) and land use and land cover change in 2040 on flow, sediment, TN, and TP under RCP 4.5 for Cool/wet; Cool-dry; Hot-wet; Hot-dry; Middle; and ensemble of climate regimes.

Climate	Water quality	Standardized coefficient		p-values		Partial correlation %	
Regimes	Parameter	Land use	Climate	Land use	Climate	Land use	Climate
Cool-wet	Flow	-0.01	0.44	0.91	0.00	-1.20	43.90
Cool-dry	Flow	-0.09	-0.06	0.42	0.58	-9.30	-6.30
Hot-wet	Flow	0.34	0.45	0.00	0.00	39.00	49.20
						-	
Hot-dry	Flow	-0.25	-0.45	0.01	0.00	28.30	-47.10
Middle	Flow	0.38	0.10	0.00	0.34	37.70	11.10
Ensemble	Flow	0.04	0.08	0.50	0.22	4.10	7.60
Cool-wet	TSS	0.08	0.06	0.50	0.58	7.70	6.30
Cool-dry	TSS	0.04	0.03	0.04	0.03	3.80	3.10
						-	
Hot-wet	TSS	-0.18	0.08	0.12	0.50	17.70	7.90
Hot-dry	TSS	0.00	0.07	0.98	0.55	0.20	6.90
Middle	TSS	0.12	0.10	0.30	0.39	12.10	10.00
Ensemble	TSS	0.04	0.10	0.57	0.11	3.40	9.70
Cool-wet	TN	0.26	0.10	0.02	0.07	26.70	20.50
Cool-dry	TN	0.03	-0.34	0.82	0.00	2.60	-33.50
Hot-wet	TN	0.40	-0.02	0.00	0.88	39.80	-1.70
						-	
Hot-dry	TN	-0.15	-0.10	0.19	0.41	15.20	-9.50
						-	
Middle	TN	-0.25	-0.53	0.01	0.00	30.10	-55.20
Ensemble	TN	0.16	-0.98	0.09	0.12	10.40	-9.60
Cool-wet	TP	0.02	0.01	0.89	0.91	1.60	14.00
Cool-dry	TP	-0.04	-0.01	0.74	0.95	-3.80	0.80
Hot-wet	TP	0.18	-0.12	0.13	0.32	17.40	-11.60
Hot-dry	TP	-0.09	0.01	0.46	0.91	-8.60	-1.30
Middle	TP	0.00	-0.94	0.01	0.37	-0.10	-4.30
Ensemble	TP	0.02	0.03	0.76	0.64	1.90	2.90

Similarly, results in Table 7.10 indicate that both climate and LULCC will have significant impacts ($p < 0.05$) on stream flow for all the regimes except under Cool-wet and ensemble; on TN under Cool-wet, Hot-dry, middle, and ensemble. However, only LULCC will significantly impact TP loads under Hot-dry condition. Like under RCP 4.5, Table 7.10 show that climate

change is likely to have a higher impact on stream flow than LULCC whereas the latter will have higher impact on TN under RCP 8.5. As in the previous case, the hypothesis that only climate change is likely to have a significant effect on stream flow in Sironko catchment in the future scenarios rejected. Similarly, the hypothesis that only LULCC is likely to have a significant effect on nitrogen as opposed to climate change in Sironko catchment in the future scenarios is also rejected. Considering TP in Sironko catchment in the future scenarios, LULCC will have a significant impact on TP for a middle climate regime. Again, the hypothesis that Nitrogen will significantly change in Sironko catchment in future as opposed to phosphorus in in the future scenarios is still rejected.

Table 7.10: Contribution of near future (2025-2040) climate and LULCC in 2040 on stream flow, sediment/TSS, TN, and TP under RCP 8.5 for Cool/wet; Cool-dry; Hot/wet; Hot-dry; Middle; and ensemble of climate regimes.

Climate	Water	RCP 8.5					
regimes	quality	Standardized Coefficient		p-values		Partial correlations (%)	
	variables	Land use	Climate	Land use	Climate	Land use	Climate
Cool-wet	Flow	0.05	0.59	0.62	0.00	5.80	59.20
Cool-dry	Flow	-0.24	-0.42	0.00	0.09	-26.80	-44.50
Hot-wet	Flow	0.29	0.52	0.00	0.00	35.00	54.80
Hot-dry	Flow	-0.29	-0.48	0.00	0.00	-34.00	-50.70
Middle	Flow	0.34	0.24	0.00	0.026	35.30	25.40
Ensemble	Flow	0.01	0.07	0.84	0.29	1.30	6.50
Cool-wet	TSS	0.08	0.07	0.49	0.55	8.00	7.00
Cool-dry	TSS	0.03	0.02	0.83	0.85	2.50	-2.20
Hot-wet	TSS	-0.05	0.06	0.65	0.58	-5.30	6.40
Hot-dry	TSS	-0.02	0.06	0.86	0.61	-2.10	5.70
Middle	TSS	0.37	-0.05	0.37	0.65	10.50	-5.30
Ensemble	TSS	0.03	0.03	0.64	0.71	2.90	2.30
Cool-wet	TN	0.70	-0.49	0.00	0.00	74.40	-61.40
Cool-dry	TN	-0.15	-0.36	0.16	0.00	-16.10	-36.60
Hot-wet	TN	0.21	0.09	0.07	0.42	21.10	9.40
Hot-dry	TN	-0.23	-0.39	0.03	0.00	-25.30	-39.80
Middle	TN	-0.38	-0.48	0.00	0.00	-37.70	-47.70
Ensemble	TN	0.20	0.17	0.00	0.01	20.20	-17.00
Cool-wet	TP	0.09	0.05	0.44	0.68	9.00	4.70
Cool-dry	TP	-0.12	0.05	0.36	0.67	-10.60	4.90
Hot-wet	TP	0.12	-0.08	0.32	0.49	11.50	-8.00
Hot-dry	TP	-0.07	-0.01	0.05	0.90	-7.60	-1.40
Middle	TP	0.06	-0.06	0.59	0.60	6.20	-6.10
Ensemble	TP	0.02	0.02	0.73	0.72	2.10	-2.20

7.9 Discussion of results

Monitoring sites 5, 6, and 7 had higher fecal coliforms number, TSS and TDS concentrations, and turbidity levels. Fecal coliforms numbers were very high in wet season compared to dry season. This is result urbanization as evidence by the huge increase in built-up areas over the

study period. Runoffs carry these contaminants from domestic and urban areas into River Sironko. Other land use land cover activities such as intensive use of agricultural lands, cultivation on steep slopes and economic activities such as sand mining and can also explain the results of this study especially, the high concentrations of TSS and TDS in River Sironko water. It should be noted that earlier study by Turyahabwe et al. (2020), attributed the pollution in River Sironko to sand mining, disposal of organic waste from home states and urban areas, discharge of effluent and sewerage from Sironko town council. The results also suggest that human factors such as application of chemical fertilizer on agricultural land, untreated domestic and industrial wastes, in addition of phosphorus as a result of atmospheric deposition are responsible for River water quality which also agrees with the finding by Ojok et al., (2019) in River Rwizi in Western Uganda. The study did not find excess phosphorus concentration in River Sironko. This is an indication that application of phosphate fertilizers on agricultural lands within Sironko catchment are still minimal or that most of the phosphorus applied have been taken up by plants. However, SWAT prediction suggests significant increase in nitrogen concentration in River Sironko which is related to land use land cover in the near future. The study also found that agricultural lands within Sironko catchment are being used intensively without giving time for fallowing as reported in earlier studies of (Mugagga et al., 2015, 2012). As the soil nutrients gets depleted, farmers will try to increase on the productivity of their land by application of chemical fertilizer and other agrochemicals hence the predicted increase in nutrient concentration in River Sironko between 2025-2040.

The water of River Sironko is used for domestic and urban water supply, fishing, small scale irrigation, livestock watering and recreational activities among others. The implications of degrading water quality in Sironko catchment in relations to the results of this study and in agreement with previous studies is that population pressure is driving rapid land use changes in Mt. Elgon region and all the available lands are intensively cultivated including the steep slopes and river banks (Mugagga et al, 2015; Mugagga et al., 2012). This study found high concentrations of TSS and TDS which confirmed problems of sedimentation, river siltation downstream, and water quality degradation in most of the rivers of Mt. Elgon as reported by (Turyahabwe et al, 2020).

This study found that in Sironko catchment, both climate LULCC will lead to significant and non-significant changes in stream flow, sediment/TSS, TN, and TP in the medium timescale 2025-2040 relative to the baseline 1980-2009 period depending on the GCMs and the scenarios. Of equally great importance, this study has also revealed that although both climate and land use changes will have significant impacts on stream flow, sediment/TSS, TN, and TP in the medium timescale, climate change will have greater contributions on stream flow than LULCC under both RCP 4.5 and RCP 8.5 whereas, the latter will strongly influence TN flux more than climate change. The World Bank (2008) had projected that future provision of clean water in Mt. Elgon region will get and our study still confirmed this in Sironko catchment based on the result of TSS, TP and TN projected between 2025-2040 by this study. More so issues of increasing demand and declining/reducing amount of clean fresh water as a result of contamination from unprotected water catchments and poor sanitation especially in situation of increased rainfall intensity was also reported (World Bank, 2008). The current study also projected significant increase in mean temperature across Sironko catchment. This temperature increase can increase biodegradation and compound water quality problems in low-lying parts of the catchment (World Bank, 2008).

Another key result of this study is that LULCC will significantly increase TN in Sironko catchment between 2025-2040 more than climate change under both RCP 4.5 and RCP 8.5. The finding agrees with Khoi et al. (2019) who found that sediment and nutrient loads were more sensitive to land use land cover change than climate change in the LA Buong River Basin in Southern Vietnam found. Furthermore, Zhang et al. (2013) argued that increase in stream flow as a result of coupled impacts of climate and land use land cover changes amplify non-point sources pollution of surface water systems from Nitrogen (N), Phosphorus (P), and sediment. Elsewhere, Shrestha et al, (2017) found that future land use slightly altered annual and seasonal water yield and nutrient loads while future climate significantly altered flow and nutrient loads under both RCP 4.5 and RCP 8.5 especially in the spring season. Sironko catchment is predominantly an agricultural catchment (agricultural lands constituted 36 % of the total catchment area) which is also undergoing rapid urbanization. It is also important to note that although SWAT has the capability of depicting the effect of climate change on agricultural activities, this could lower because of land use land cover and climate change whereby some nutrients are taken up by plants on an agricultural land and others eroded into River Sironko an effect of climate change

(high precipitation. Similar finding was reported in the Neshanic River Watershed in central New Jersey USA by Giri, Arbab, & Lathrop, (2019). The findings of this study however, contradict Khoi et al. (2019) who found stream flow to be more sensitive to land use change than climate change in the LA Buong River Basin in Southern Vietnam. It is therefore possible that the observed increase in stream flow, sediments and nutrients loading under Cool/wet, Hot/wet and Middle climate regimes are due to transformation of forests, woodlands, and wetlands into agricultural land and built-up areas which are good sources of the above pollutants. In chapter four, it was reported that between 1986-2000 agricultural lands decreased by 7.5 %, forests by 32.6%, and wetlands by 20.3% at the expense of bare lands, built-up areas and woodlands. However, it is projected that built-up areas will increase by 74 % in Sironko catchment by 2040 and agricultural lands by 5% whereas, wetlands will decrease by 9 %, and woodlands by 7 %. Kroese et al. (2020) found that agricultural land is the main source of sediments and nutrients loads into stream water followed by forests conversion in the highlands of Kenya, In the study of Misganaw & Aramde, (2019) in the Gojeb Watershed, Omo-Gibe basin of Ethiopia, it was reported that increased agriculture at the expense of forest resulted in an increase in stream flow and sediment yields of 8.6 m³/s and 41.07 ton/km² respectively. In the upper reaches of the Umngeni catchment in south Africa meanwhile, Namugize et al., (2018) reported that increased agriculture and urban areas at the expense of natural vegetation increased nutrients enrichment in water supply reservoirs in the catchment by 20 %.

Mt. Elgon region where Sironko catchment is located lies within a fragile ecosystem where rapid LULCC has been reported (Mugagga et al., 2015; Mugagga et al., 2012). The area is also prone to soil erosion, landslides, floods, and drought (Knapen et al., 2006). The National Housing and Population Census Report UBOS, (2016) revealed that Mt. Elgon region in Uganda is one of the poorest and most densely populated, and rapidly urbanizing rural part of Uganda. The socioeconomic and demographic status of the people around Mt. Elgon force them to encroach on protected areas and forest reserves on the mountain, cultivate ecologically fragile areas such as steep slopes, swamps, and riverbanks (Nakileza et al., 2017). These conditions as described are other possible explanations to the projected increase in stream flow, sediment, and nutrients loads in Sironko catchment in the near future. Giri et al., (2019) argued that increased stream flow resulted in increased sediment loading possibly due to increased erosion. Flood events for example are reported to be responsible for sediments and nutrients enrichment of surface water

systems (Torma et al., 19; Mellander et al., 2018; El-zeiny et al., 2018). However, sediment, and nutrients loads in Sironko catchment have been projected to decline in the near future under RCP 4.5 and RCP 8.5 especially under Hot/dry and Cool/dry climate regimes. This is possibly a result of model's uncertainties and also due to differences between scenarios. In the Upper Ebonyi river watershed, South East Nigeria. Serpa et al., (2017), also reported that climate change led to a decline in annual total Nitrogen (TN) and total phosphorus (TP) exports under both A1B and B1 emission scenarios while land use change resulted in an increase in stream flow, but variations were observed in water quality according to the scenarios. Although no clear data exist, it is known from the knowledge of the study area that local farmers in the Mt. Elgon region are also increasingly using chemical fertilizers in efforts to maximize productivity on limited land. The increase use of fertilizers will most likely increase in the near future hence, the nutrient loads are projected to increase in the catchment in the near future. Part of the catchment is also in the cattle corridor and the projected increase in TN could as well be a contribution from livestock.

7.10 Limitations of the study

Most of the river gauges and weather stations within the Lake Kyoga basin and Uganda in general, are either partially functioning or not functioning at all. The river gauges and weather stations are either short in length, poorly managed, or have completely been vandalized (OAG, 2018). Additionally, where data exist, the data are inconsistent and many times with urged gaps that cannot be filled (OAG, 2018). The same problem is encountered when it comes to water quality monitoring data in the basin (OAG, 2018). This probably explains why most studies conducted in the Mt. Elgon region UNDP (2013); Knapen et al. (2006) have only focused on climate change, Mugagga et al. (2015); Mugagga et al. (2012) tailored to land use change without relating to impact on water quality, and Turyahabwe et al., (2020); Namaalwa et al. (2020) who investigated the impacts of land use and land cover on water quality but did not consider climate change impacts. To overcome data limitation, we used the MERRA data 1980-2009 provided by the AgMIP as bassline for medium timescale 2025-2040 climate projection. Local examples of scholars who used this similar approach include (Egeru et al., 2019; Majaliwa et al. 2015). Furthermore, the SWAT model a semi-physically, process-based model whose components includes mathematical descriptions of physical, biogeochemical and hydrochemical

processes was used. SWAT has widely been used and recommended for use in data limited catchments (Guo et al., 2019; Hülsmann et al., 2015; Nyeko, 2015; Panagopoulos et al, 2011)

7.11 Conclusions

This study determined the impacts of climate and land use change on the magnitude of selected water quality parameters on a medium timescale in Sironko catchment for the sustainability of the livelihood of local community. Selected water quality parameters that affect drinking water standards were monitored from January to December 2018 following the standard procedures for testing physico-chemical and biological water quality for drinking purposes in the field and in the laboratory. Mean values of monitored parameters in dry and wet seasons were compared against the Uganda National Bureau of Standards (UNBS) guideline while repeated measured t-test was employed at $p < 0.05$ level of significant in IBM SPSS 20 to determine any significant difference in water quality between dry and wet seasons. The LULCC of the catchment in 2040 was projected as detailed in chapter four while the climate scenarios were developed as explained in chapter six prior to simulation of stream flow, sediments/TSS, total nitrogen (TN), and total Phosphorus (TP) loads using the Soil and Water Assessment Tool (SWAT). On the basis of the key findings, this study concludes that:

1. Fecal coliforms were higher than the UNBS maximum limit in all sites during wet season.
2. Significant seasonal difference ($p < 0.05$) between dry and wet season was detected for pH, EC, TP, and DO respectively.
3. Both land use and climate change will decrease or increase stream flow, sediments/TSS, and nutrients loading in Sironko catchment at significant level ($p < 0.05$) in the medium term (2025-2040) relative to baseline (1980-2009) condition.
4. In the medium timescale 2025-2040, both climate and land use change will increase or decrease stream flow, TSS, TN, and TP loads at both significant level ($p < 0.05$) and non-significant levels depending on the model and scenarios.
5. Whereas the impacts of both climate and land use land cover on River flow are both significant at $p < 0.05$ levels between 2025 to 2040, climate change will increase River flow and more than land use land cover change while the later will increase TN more than climate change under both RCP 4.5 and RCP 8.5.

7.12 Recommendations

1. Improved sanitation facilities and proper waste management is urgently needed in Sironko catchment to curb water pollution especially during rainy season.
2. Stakeholders need to plan and mitigate the impacts of both future climate and land use change on water quality in Sironko catchment for the sustainability of water resources and livelihoods in Sironko catchment.
3. Future studies should identify best management practices to minimize the impacts of both climate and land use changes on water quality in Sironko catchment.

CHAPTER EIGHT: SYNTHESIS OF KEY FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

8.1 Introduction

Water is a resource that is highly vulnerable to the changing climate (IPCC, 2014). Climate change also affects the pattern and nature of LULCC and the hydrologic cycle through increased or decreased precipitation (Zhao et al., 2012). Investigation of LULCC at a catchment level provides essential information regarding the hydrology of the catchment. Thus, the gist of this study was to contribute to improved understanding of the impacts of climate and land use land cover changes on water quality in tropical mountain environments, based on a case study of the Sironko catchment on the slopes of Mt. Elgon in Eastern Uganda. Specifically, the study 1) Systematically reviewed and carried out a meta-analysis of land use land cover change studies in Uganda at national, regional and local scales; 2) Determined the historical and future dynamics of land use land cover change and transitions on a medium timescale in Sironko catchment; 3) Assessed the trends and magnitude of climate variation and change on a medium timescale in Sironko catchment and; 4) Determined the impact of climate and land use land cover changes on the magnitude of selected water quality properties in Sironko catchment.

8.2 Synthesis of key findings

Changes in land use and land cover coupled with the impact of climate change alter river flow (volume, timing and frequency) through the alternation of overland flow and infiltration, ground water recharge, flow velocity, sediment detachment and transportation (IPCC, 2020; Mango et al., 2011). This study found that LULCC will have a stronger signal on TN than climate change under both RCP 4.5 and RCP 8.5. Furthermore, the results showed that fecal coliforms were above UNBS allowable limit especially in the settlement/built-up areas of Sironko catchment. Turyahabwe et al., (2020), also found similar pattern of water quality pollution in Sironko catchment and attributed the pollution to sand mining, disposal of organic waste from home states and urban areas, discharge of effluent and sewerage from urban areas. Although it was not possible to correlate the model predictions with actual measurements so as to link effects of specific land use land cover types to magnitudes of selected water quality parameters, the current study reported a very high variability in stream flow, sediment loads and TP. Literature suggests

that land development (conversion of vegetation to bare land and urbanization) were the major stressors of stream water quality (Paule-mercado et al., 2018). Tuomela et al, (2019) meanwhile found that pollution loads and sediment sources were highly fragmented and variable in urban catchment hence, it was impossible to single out the specific land use land cover type with the strongest signature on water pollution. According to Salim et al., (2019), erosion and settlement (domestic wastewater) are the primary source of water pollution. On the other hand, Kroese et al. (2020) reported that agricultural land is the main source of sediments and nutrients loads into stream water followed by forests conversion in the highlands of Kenya.

In relation to climate change, this study revealed that between 2025-2040; climate change will increase stream flow more than LULCC under both RCP 4.5 and RCP 8.5 while the later will have a stronger signal on TN under both RCP 4.5 and RCP 8.5. The aggregated effects of climate and land use changes on the magnitudes of selected water quality parameters were however found to be stronger than the individual impacts. This finding agrees with, scholars like Giri et al., (2019), Ndulue & Mbajorgu (2018), and Trang et al., (2017) who reported aggravated impacts on water quality due to the interaction between climate change and LULCC. The results contradict the argument that the combined impacts climate and land use land cover changes do not necessarily result in accelerating changes in water quality (Shrestha et al., 2017; Khoi & Suetsugi, 2014). The effects of both drivers may also offset each other (Zhang et al., 2016). The contradictions are expected as argued by the IPCC, (2021) that future climate and land use land cover changes will impact water resources differently depending on the location; the current and future stocks of freshwater; and/or the climate/land use land cover scenarios under consideration. It has been argued that accounting for the impacts of climate and LULCC on water resources is perhaps one of the greatest challenges facing water resources management in the 21st century (Molina-Navarro et al., 2018; Shrestha et al., 2018; and Trang et al., 2017). According to Scott et al., (2019); Terzi et al., (2019); Palomo, (2017), the interactions between climate and land use land cover changes are even more complex and with multiple cascading effects in mountain ecosystems.

8.3 Conclusions

Having synthesised the findings of the specific objectives (1-4), this study concluded that:

1. Population pressure is the key driver of land use land cover change in Uganda
2. Agricultural lands in Sironko catchment are being intensively cultivated without giving it time to fallow.
3. Between 1986 and 2000, agriculture was expanding in forests and wetlands but this change between 2000 and 2016 due to eviction and conservation efforts.
4. SON seasonal rainfall in Sironko catchment is highly variable as compared to MAM seasonal rainfall.
5. Seasonal and annual rainfall with significantly increase in Kumi and Nakapiripirit station between 2025 and 2040
6. Significant increase in mean temperature is projected across Sironko catchment between 2025-2040
7. Future climate and land use change are likely to exacerbate floods, water quality deterioration and waterborne diseases in Sironko catchment and Mt. Elgon region.
8. Changing climate is likely to result in warmer temperatures, more evaporation, less infiltration, less soil moisture, less ground water recharge, less stream flow, more variations in rainfall and stream flow and increased water pollution.
9. Under the background of increasing population, demand, and increased pollution, more people in the region will be affected by water scarcity.

8.4 Recommendations

Based on the key findings and conclusions of this study, it is recommended that:

1. Diversification of livelihood means for example bee keeping and poultry rearing would offset the role of crop production as the most dominate livelihood mean and parts of cultivated land could be allowed to fallow.
2. More studies are needed in Mt. Elgon region to identify best management practices (BMPs) to mitigate future impacts of climate and land use changes on water quality. BMPs applied at the catchment level wills improved water quality management in Sironko catchment.
3. More innovations will be needed for water conservation, enhance supply, and more efficiently manage the water resources within Sironko catchment and Mt. Elgon region.
4. Practices such as agricultural water conservation and water reuse, watershed management, improved waste management, and protection of river banks will improve water quality management in the catchment, reduce the risk of waterborne diseases, reduce water treatment cost, and possibly lower water bills in future in addition improving on the ecosystem health.

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APPENDICES

Appendix 1: The selected and reviewed articles (1998-2018)

S/No	Author(s) and date	Focus of the studies
1	Akello et al., (2016)	Status of Awoja catchment.
2	Anaba et al., (2017)	Water quality under various land use
3	Barasa et al., (2010)	Land use/cover changes dynamics
4	Berakhi et al., (2013)	Land use/ cover and human activates
5	Bruce Rukundo (2013)	Land-Use and Forest-Cover Change in Kibaale District
6	Byenkya et al., (2014)	Extent of land use and cover change and their impacts on livestock management under drought induced pasture
7	Ebanyat et al., (2010)	Land use change and drivers
8	Egeru et al., (2010)	Effect of Land use/cover change on Biomass Stock
9	Egeru et al., (2014)	Spatial-temporal dynamics of forage and land cover changes
10	Fura (2013)	Land cover modelling
11	Gorsevski et al., (2012)	Effect of armed conflict on forest ecosystem
12	Hatter & Southworth, (2009)	Forest change
13	Hatter (2007)	Impacts of land use and cover change on livelihoods
14	Isunja & Kemp (2016)	Wetland change
15	Jacob et al., (2013)	Resolving land cover misclassification
16	Jagger & Shively (2014)	Biomass supply, consumption and land use change
17	Jagger et al., (2018)	Conservation management impacts
18	Kiggundu et al., (2018)	Land use/cover changes
19	Kizza et al., (2017)	Land use/cover change
20	Li et al., (2016)	Historical and future land use changes in Uganda
21	Lindblade et al., (1998)	Land use change, farm management and impacts
22	Lung & Schaab (2010)	Land cover dynamics and drivers
23	Maitima et al., (2010)	Land use change, impacts and opportunities
24	Majaliwa et al., (2010)	Land-use /cover change effects on properties of soils
25	Majaliwa et al., (2018)	Assessed the extent of historical, current, and future land use systems in Uganda
26	Mbaziira 2014	Effects of land use and cover change on rangeland ecosystem
27	Mugagga et al., (2012)	Land use changes and landslides occurrences
28	Mugagga, (2015)	Land use change, carbon stocks and climate variability.
29	Mwavu & Witkowski (2008)	Land use/cover change
30	Mwavu et al., (2018)	Commercial agriculture vs food security
31	Nakakaawa, Vedeld &	Quantify and map major land use and land cover

	Aune (2011)	(LULC) change patterns
32	Nakalembe et al., (2017)	Land use change and drivers
33	Nyeko (2010)	Land use changes and water resources management
34	Otukey & Blaschke (2010)	Land cover change detection using combination of methods
35	Sassen et al., (2013)	Forest cover change and drivers
36	Ssentongo et al., (2017)	Forest cover change and ecosystem services
37	Tolo, Majule & Perfect (2012)	Trend of natural resources degradation
38	Twongyirwe et al., 2011	Forest change and drivers
39	Twongyirwe et al., 2015	Spatial and temporal heterogeneity of the land cover changes
40	Wadembere & Kobugabe (2017)	Urbanization and its effects
41	Wandera (2014)	Causes of land use changes and stakeholders' perceptions
42	Zhang et al., (2017)	Carbon stocks and land cover

Appendix 2. Land use and land cover classes used in the classification of images

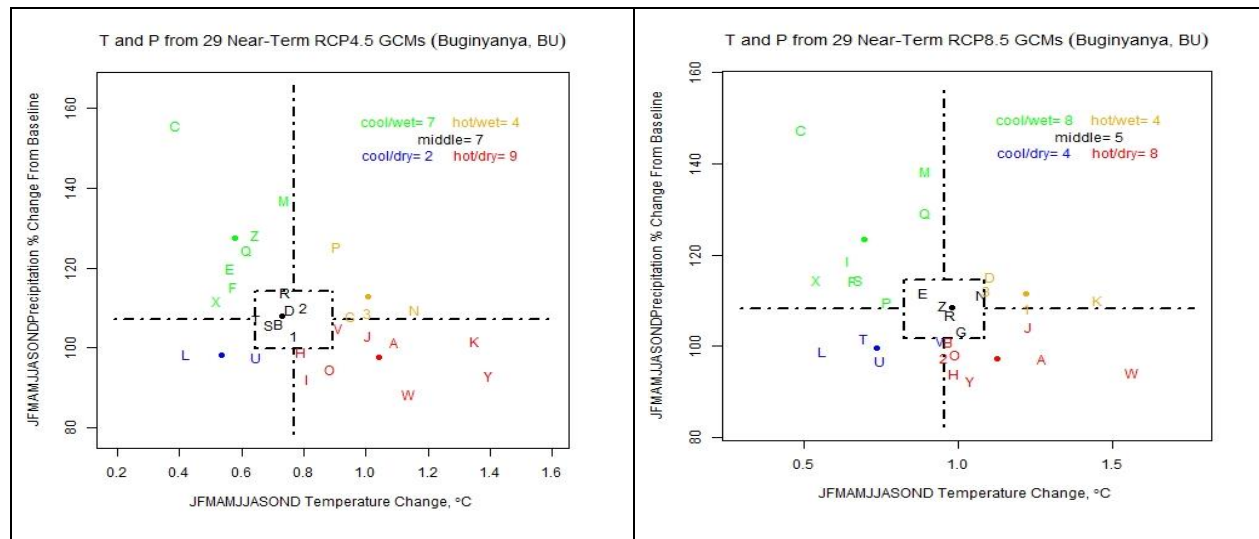


Appendix 3: Global Circulation models (GCMs) used in the downscaling of near future climate in Sironko catchment.

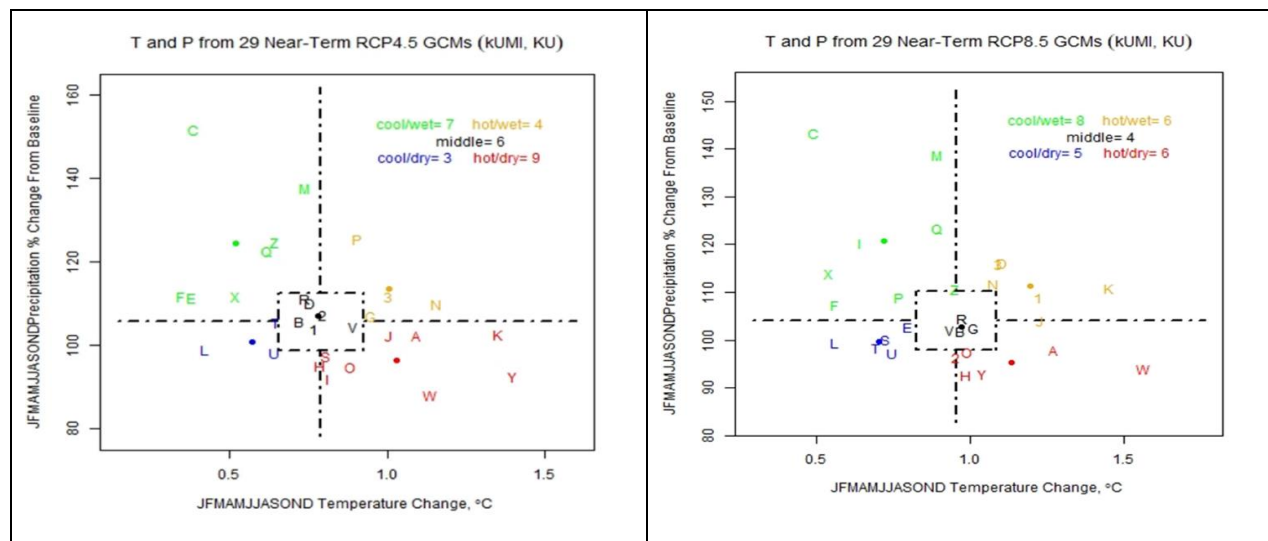
GCMs	Institution
A = ACCESS1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
B = bcc-csm1-1	Beijing Climate Center, China Meteorological Administration
C = BNU-ESM	College of Global Change and Earth Systems Science, Beijing Normal University (BNU)
D = CanESM2,	Canadian Centre for Climate Modelling & Analysis
E = CCSM4	US National Center for Atmospheric Research (NCAR)
F = CESM1-BGC	US National Science Foundation (NSF), US Department of Energy (DOE), and the US National Centre for Atmospheric Research (NCAR)
G = CSIRO-Mk3-6-0	Queensland Climate Change Centre of Excellence and Commonwealth Scientific and Industrial Research Organization (CSIRO)
H = GFDL-ESM2G	NOAA/Geophysical Fluid Dynamic Laboratory (GFDL)
I = GFDL-ESM2M	NOAA/Geophysical Fluid Dynamic Laboratory (GFDL)
J = HadGEM2-CC	UK Meteorological Office - Hadley Centre
K = HadGEM2-ES	UK Meteorological Office - Hadley Centre
L = inmcm4	Russian Institute for Numerical Mathematics (INM)
M = IPSL-CM5A-LR	Institute Pierre Simon Laplace (IPSL)
N = IPSL-CM5A-MR	Institute Pierre Simon Laplace (IPSL)
O = MIROC5	University of Tokyo, Japanese National Institute for Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
P = MIROC-ESM	University of Tokyo, Japanese National Institute for Environmental

	Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
Q = MPI-ESM-LR	Max Planck Institute (MPI) for Meteorology (low resolution)
R = MPI-ESM-MR	Max Planck Institute (MPI) for Meteorology (mixed resolution)
S = MRI-CGCM3	Japanese Meteorological Research Institute (MRI)
T = NorESM1-M	Norwegian Climate Centre
U = FGOALS-g2	Chinese Academy of Sciences
V = CMCC-CM	Euro-Mediterranean Center on Climate Change
W = CMCC-CMS	Euro-Mediterranean Center on Climate Change
X = CNRM-CM5	France National Centre for Meteorological Research
Y = HadGEM2-AO	UK Meteorological Office - Hadley Centre
Z = IPSL-CM5B-LR	Institute Pierre Simon Laplace (IPSL)
1 = GFDL-CM3	NOAA/Geophysical Fluid Dynamic Laboratory (GFDL)
2 = GISS-E2-R	National Aeronautics and Space Association Goddard Institute for Space Studies (NASA GISS)
3 = GISS-E2-H	National Aeronautics and Space Association Goddard Institute for Space Studies (NASA GISS)

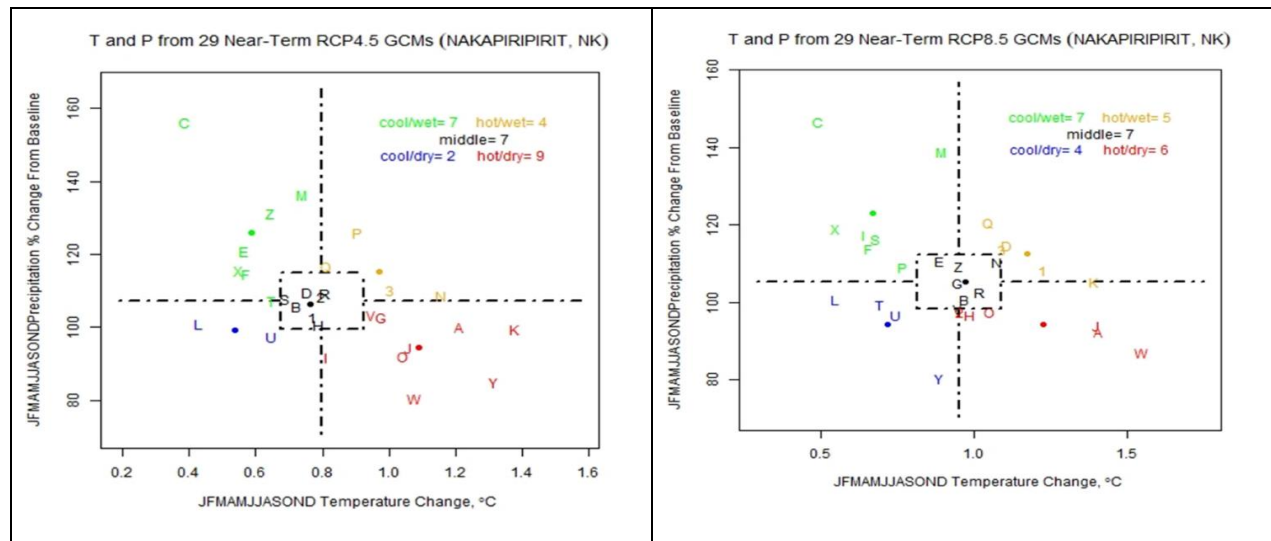
Appendix 3: GCMs selection using the representative temperature and precipitation change GCMs sub-setting approach for RCP 4.5 and RCP 8.5 for the near future for Buginyanya.



Appendix 5: GCMs selection using the representative temperature and precipitation change GCMs sub-setting approach for RCP 4.5 and RCP 8.5 for the near future for Kumi



Appendix 6: GCMs selection using the representative temperature and precipitation change
GCMs sub-setting approach for RCP 4.5 and RCP 8.5 for the near future for Nakapiripirit



Appendix 7: Selected GCMs in Buginyanya, Kumi, and Nakapiripirit stations for the 2025-2040 period under RCP 4.5 and RCP 8.5 scenarios

Stations	Scenarios	Cool/wet	Hot/wet	Cool/dry	Hot/dry	Middle
Buginyanya	4.5	MPI-ESM-LR	GISS-E2-H	ACCESS1-0	FGOALS-g2	CanESM2
	8.5	GFDL-ESM2M	bcc-csm1-1	MIROC5	FGOALS-g2	IPSL-CM5B-LR
Kumi	4.5	CESM1-BGC	IPSL-CM5A-MR	MPI-ESM-LR	FGOALS-g2	CSIRO-Mk3-6-0
	8.5	ACCESS1-0	GFDL-ESM2M	bcc-csm1-1	FGOALS-g2	CMCC-CM
Nakapiripirit	4.5	CESM1-BGC	BNU-ESM	MIROC-ESM	FGOALS-g2	ACCESS1-0
	8.5	CESM1-BGC	CanESM2	MPI-ESM-LR	FGOALS-g2	CMCC-CM
Outlet	4.5	CESM1-BGC	IPSL-CM5A-MR	MPI-ESM-LR	FGOALS-g2	CSIRO-Mk3-6-0
Outlet	8.5	CESM1-BGC	GFDL-CM3	GISS-E2-R	FGOALS-g2	CMCC-CM

Appendix 8. Stream flow sensitivity analysis parameters

Parameters	Definition	Fitted Value	Minimum value	Maximum value
CN2	SCS runoff curve number (dimensionless)	-31.52	-31.56	-31.07
ALPHA_BF	Base flow alpha factor (days).	0.74	0.74	0.75
GW_DELAY	Groundwater delay (days).	277.25	275.85	279.22
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm).	1673.23	1651.24	1706.62
SURLAG	Surface runoff lag time.	10.83	10.79	11.26
SHALLST	Initial depth of water in the shallow aquifer (mm).	27049.88	27012.34	27407.54
DEEPST	Initial depth of water in the deep aquifer (mm).	11467.94	11267.80	11646.14
GW_REVAP	Groundwater "revap" coefficient (dimensionless).	0.13	0.13	0.13
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm).	234.57	234.22	237.71
RCHRG_DP	Deep aquifer percolation fraction (dimensionless).	0.55	0.54	0.55
GWHT	Initial groundwater height (m).	14.44	14.19	14.56
CH_K2	Effective hydraulic conductivity in main channel alluvium (mm/h).	0.00	0.00	0.01
SOL_AWC(..)	Available water capacity of the soil layer (mm H ₂ O/mm Soil).	-0.11	-0.27	-0.10
SOL_K(..)	Saturated hydraulic conductivity (mm/h).	12.34	10.65	12.38
CH_N2	Manning's "n" value for the main channel (dimensionless).	0.21	0.21	0.23
OV_N	Manning's "n" value for overland flow.	15.22	15.20	15.66
HRU_SLP	Average slope steepness	0.70	0.70	0.72
ESCO	Soil evaporation compensation factor (dimensionless).	-0.09	-0.10	-0.09

Appendix 9: Sensitivity ranking of stream flow parameters in Sironko catchment

Parameter Name	t-Stat	P-Value	Ranking
SOL_AWC(..)	51.1404	0.0000	1
CH_N2	45.9069	0.0000	2
SOL_K(..)	-19.8824	0.0000	3
ESCO	-3.9487	0.0001	4
DEEPST	-1.4181	0.1568	5
GW_REVAP	-1.3318	0.1836	6
CH_K2	1.0244	0.3061	7
SURLAG	-0.9539	0.3406	8
ALPHA_BF	-0.8195	0.4129	9
GWHT	0.7966	0.4261	10
REVAPMN	-0.7000	0.4843	11
RCHRG_DP	0.5417	0.5883	12
OV_N	-0.4937	0.6217	13
GW_DELAY	0.3028	0.7621	14
SHALLST	0.2812	0.7787	15
GWQMN	-0.1950	0.8455	16
CN2	0.0656	0.9477	17
HRU_SLP	-0.0552	0.9560	18